



3DxVERSE

Work Package 8

D8.4: Digital Twin for Sustainable Airport, Mobility and Living Environment - First Report

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3DxVERSE project is co-funded by the European Union's Digital Europe Programme (DIGITAL) under grant agreement No. 101168258.

History of changes

Work Package	WP8
Task 8.2	Digital Twin for Sustainable Airport and Living Environment
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Dissemination Level	Public
Status	Report
Due date	30/11/2025
Document Date	30/11/2025
Version Number	1.0

Quality Control

	Name	Organisation	Date
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Peer review 2	Nicky Hickman	iLabs	20/11/2025
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LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviation	Meaning
3DxVERSE	Digital Twins for Sustainable Travel and Living Communities
AAA	Aruba Airport Authority
ACA	Airport Carbon Accreditation
ACI	Airports Council International
ADS-B	Automatic Dependent Surveillance–Broadcast
AEDT	Aviation Environmental Design Tool
AHOP	Aruba Happy One Pass
AI	Artificial Intelligence
AODB	Airport Operational Database
AOS	Airport Operational System
API	Application Programming Interface
APU	Auxiliary Power Unit
ATA	Aruba Tourism Authority
BMS	Building Management System
BVM	Hamburg Ministry of Transport and Mobility Transition
CAT021	EUROCONTROL Surveillance Data Exchange Format
CCAM	Cooperative Connected and Automated Mobility
CO₂	Carbon Dioxide
CO₂ VC	Carbon Dioxide Verifiable Credential
DGA	Data Governance Act
DLT	Digital Ledger Technology
DPIA	Data Protection Impact Assessment
ENISA	European Union Agency for Cybersecurity
ESRI	Environmental Systems Research Institute
ESSIF	European Self-Sovereign Identity Framework
ETL	Extract–Transform–Load
EU	European Union
FCD	Floating Car Data
FHC	Future Holding Company N.V.
GDPR	General Data Protection Regulation
GHG Protocol	Greenhouse Gas Protocol
GLOSA	Green Light Optimal Speed Advisory
GNSS	Global Navigation Satellite System
GPU	Ground Power Unit
GSE	Ground Support Equipment
HPA	Hamburg Port Authority
IDTT	Interoperable Digital Twin Testbed
ITS	Intelligent Transport Systems
KPI	Key Performance Indicator
LAeq / SEL / Lmax	Acoustic Metrics Used in Noise Monitoring
LCMM	Low Carbon Mobility Management
LDT	Local Digital Twin
MAU	Monthly Active Users
MIMs	Minimum Interoperability Mechanisms
NGSI-LD	FIWARE Standard for Context Information Management
NOx/SOx/PM	Nitrogen Oxides / Sulphur Oxides / Particulate Matter
OASC	Open and Agile Smart Cities
OLS	Obstacle Limitation Surfaces
PIA	Privacy Impact Assessment
RBAC	Role-Based Access Control
SDG	Sustainable Development Goals
SLA	Service Level Agreement

SPaT / MAP	Signal Phase and Timing / Map Data
TF	Trust Framework
THUAS	The Hague University of Applied Sciences
UC	Use Case
WEB	Water- en Energiebedrijf Aruba
WLTP	Worldwide Harmonised Light Vehicle Test Procedure
WP	Work Package

EXECUTIVE SUMMARY

Deliverable D8.4 presents the first implementation stage of the 3DxVERSE Digital Twin pilots in Hamburg, Aruba, and Timișoara. It builds on the use-case design in D6.2 and the technical integration work in D7.3, translating them into operational pilot setups that combine real data sources, early modelling, and engagement processes. The deliverable explains how each pilot prepares for the transition from static Local Digital Twins (LDTs) to semi-dynamic environments, using harmonised data models, shared standards, and common governance frameworks.

Chapter 1 introduces the 3DxVERSE vision, highlighting how Local Digital Twins support sustainable travel and living communities by integrating real-world data, simulation, visualisation, and user engagement. It explains that D8.4 represents the initial implementation and evaluation phase, building directly on the use-case design of D6.2 and the testbed integration in D7.3. The chapter clarifies the purpose of D8.4: to show how the theoretical frameworks are applied in practice across the three pilots, moving from design to operational readiness. It also maps the interdependencies of WP8 with WP1–WP7 and lists the T8.2 task's objectives, including updating use cases, defining data sources, describing implementation stages, presenting early simulations, and setting the KPI evaluation framework.

Chapter 2 focuses on the sustainable mobility pilots for Hamburg, Aruba and Timișoara. It describes how these cities apply Local Digital Twins to support sustainable mobility planning, emission reduction and data-driven decision-making. The chapter provides an overview of the policy context and practical scope of the mobility pilots, explaining how they combine relevant datasets such as LCMM, Floating Car Data and SPaT/MAP timing information. It discusses the participating stakeholders and describes the modelling and simulation approaches that can be used to understand traffic behaviour, emissions, travel patterns and urban mobility trends. The chapter sets out a clear implementation framework structured in stages, beginning with a Static Local Digital Twin based on harmonised historical datasets, moving towards a Semi-Dynamic LDT with periodic updates, and eventually progressing to a scale-out phase. It concludes with the mobility KPI framework, which prepares the pilots for future performance measurement.

Chapter 3 describes the implementation framework for the Queen Beatrix International Airport (AUA) pilot in Aruba. It defines the operational roadmap for establishing a comprehensive Digital Twin that integrates airside operations, noise monitoring, and passenger engagement via the AHOP CO2 Wallet. This chapter details the governance structure, the specific data architecture required for the four airport use cases (UC4–UC7), and the phased implementation plan (Foundations to Expansion) that will guide the pilot toward Airport Carbon Accreditation (ACA) Level 4 support.

Chapter 4 summarises the validation status of the first implementation stage and explains how the results of D8.4 will feed into subsequent deliverables, including the semi-dynamic deployment planned for the next reporting period. It reaffirms that the pilots have established the necessary foundations for Local Digital Twins, with identified datasets, validated data pipelines, early models and initial user-engagement components already in place.

1. INTRODUCTION

1.1. Introduction to 3DxVERSE

The 3DxVERSE project aims to harness the potential of Digital Twins to foster sustainable travel and living communities. The initiative focuses on key use cases at various levels, from airports to living communities, encompassing sustainability, economic growth, societal development, safety, security, resilience, and corporate sustainability responsibility in a holistic approach. By establishing interoperable Digital Twins and leveraging cutting-edge technologies like AI, XR/VR and Data Spaces, this project aligns with the New European Bauhaus initiative and the G20 Framework for Systems of Digital Public Infrastructure.

Through potential collaboration with organisations like the International Data Spaces Association, Open & Agile Smart Cities (OASC) working on the OASC Minimal Interoperability Mechanisms (MIMs), and European Digital Infrastructure Consortia (EDIC's), we seek to create a transformative impact on digital inclusion, innovation, and sustainability, contributing to the achievement of the 2030 Agenda for Sustainable Development.

By creating an open, interoperable, secure, trustworthy, fair and inclusive reference implementation blueprint Digital Twin for EU citizens, businesses and public administrations, this project strives to build a resilient, inclusive, and environmentally conscious digital economy and society.

The project places a strong emphasis on societal impact, inclusive economic growth, and long-term sustainability; core values that align closely with the United Nations Sustainable Development Goals (SDGs) and the European Union's vision for a green and digital transition.

To achieve this, we are collaborating with a diverse network of international partners and pioneering cities that are actively shaping the future of digital urban ecosystems. These include Almelo in the Netherlands, Hamburg in Germany, Timișoara in Romania, and Oranjestad in Aruba. Each city brings unique regional challenges and innovative approaches, enriching the project's scope and reinforcing our shared commitment to building interoperable, citizen-centric Local Digital Twins across varied socio-economic and geographic contexts.

1.2. Purpose of the deliverable

Deliverable D8.4 represents the initial implementation and evaluation phase of the Digital Twin pilots initiated under the 3DxVERSE project. Building upon the foundations established in deliverable D6.2, this document translates the theoretical design, interoperability frameworks, and simulation concepts into initial plan for the operations of pilot environments for Aruba and Hamburg and sets the stage for further replication in Timișoara.

Where D6.2 provided the conceptual blueprint and technological roadmap for Digital Twin development, D8.4 demonstrates how these concepts are applied in practice by integrating real-world data, multi-source interoperability testbeds, and stakeholder engagement mechanisms to deliver measurable improvements in sustainability, efficiency, and citizen participation.

It serves as both implementation and evaluation frameworks, consolidating results from the current pilot deployments within the overarching 3DxVERSE architecture.

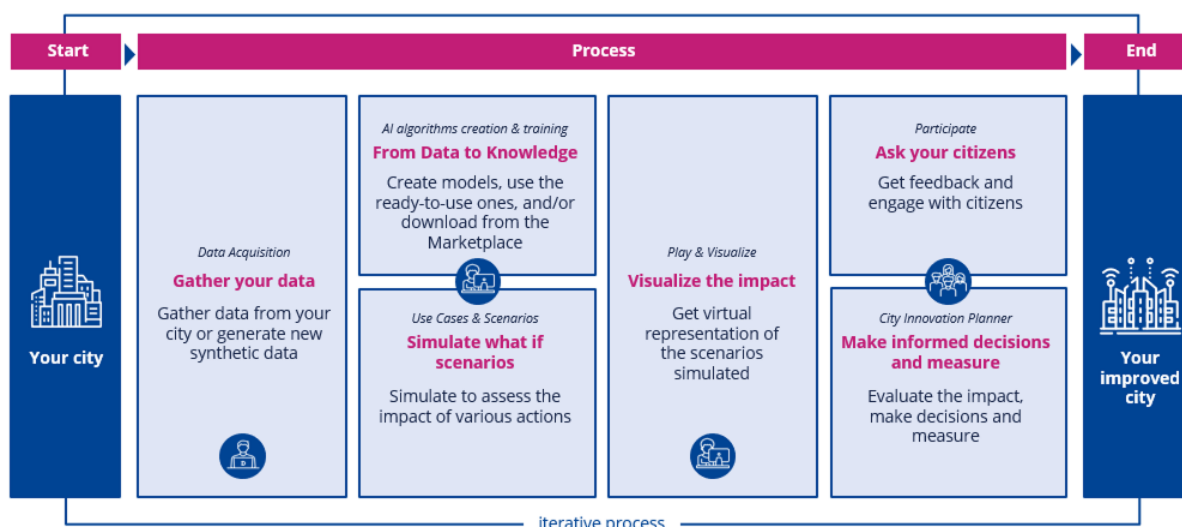


Figure 1: Data-to-decision lifecycle

In line with the data-to-decision lifecycle illustrated in the 3DxVERSE methodology (Figure 1), the purpose of D8.4 is to showcase how pilot cities move from data acquisition to knowledge generation, simulation, visualization, user engagement, and decision-making through iterative digital-twin processes that improve local ecosystems.

Through these objectives, D8.4 fulfills a bridging function within the 3DxVERSE lifecycle: it connects the design and modeling work of WP6 and WP7 with the practical implementation and citizen-engagement activities of WP8, while feeding validated outcomes back into the governance, trust, and interoperability frameworks of WP5.

Ultimately, this deliverable provides the European Commission and project stakeholders with evidence of implementation maturity, demonstrating how the 3DxVERSE architecture enables secure, interoperable, and human-centered Digital Twins that can be reused and scaled across European cities.

1.3. Interdependencies with other work packages

Work Package 8 (WP8) – Pilots and Citizen Engagement – is positioned at the application and validation layer of the 3DxVERSE architecture, as illustrated in Figure 2. It operationalizes and evaluates the Digital Twin frameworks, models, and governance mechanisms developed in the project’s technical core (WP3–WP7), translating them into practical implementations within real pilot environments.

Table 1: Dependencies between WP8 and other

Work Package	Main Contribution to WP8	Feedback from WP8 (Pilots)
WP1 – Ethics	Ethical, privacy, and consent requirements	Evidence of compliance and citizen engagement feedback
WP2 – Coordination	Project management, QA, and reporting	Pilot progress metrics and RAID updates
WP3 – Interoperability Architecture	Reference models, NGSI-LD standards, and all other interoperability architectures.	Validation of architecture and performance
WP4 – Digital Commons	Ethical governance and participation principles	Real-world citizen engagement results

WP5 – Trust & Security	iSHARE-based Trust, DevSecOps and Privacy and security by design frameworks	Implementation evidence and security evaluation
WP6 – Use Case Design	Use-case structure, KPIs, and datasets	Operational validation and performance results
WP7 – Testbed Integration	Technical testbed and data pipeline	Interoperability testing feedback
WP9 – Dissemination & Exploitation	Communication channels and outreach	Pilot visuals, results, and lessons learned

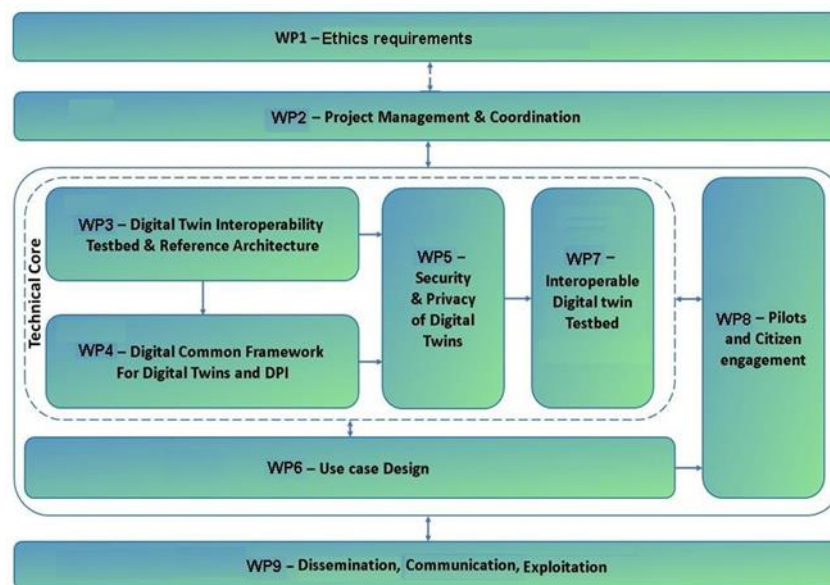


Figure 2: Interdependencies between work packages in the 3DxVERSE project

1.4. Intended audience

The dissemination level of D8.4 is ‘Public’ (PUB) and it is available to the members of the consortium, the European Commission (EC) services and those external to the project.

This document is primarily intended to serve as an internal guideline and reference for all 3DxVERSE beneficiaries, especially the governance bodies such as the General Assembly, the Steering Committee, the Technical Management Team, and the Advisory Board.

1.5. Objectives of the deliverable

The main objective is to demonstrate and evaluate the current progressions of the deployment of Digital Twin ecosystems in Aruba, Hamburg and Timisoara, validating how these environments contribute to sustainability, operational efficiency, and user engagement through secure, interoperable, and ethical data use.

Aligned with the overall goals of 3DxVERSE, the specific objectives of D8.4 are:

1. Provide an operational framework for realizing mobility and airport use cases.
2. Update pilot use cases to reflect the latest developments, ensuring consistency with current data models, standards, and pilot progress.

3. Describe the multi-level implementation framework guiding the transition from static to dynamic Local Digital Twins.
4. Describe key data sources and specifications used in all pilots.
5. Demonstrate user and citizen engagement.
6. Present early simulation results from the first project iteration.
7. Define an evaluation framework with measurable KPIs covering operational, environmental, and social impacts.
8. Feed pilot results forward into subsequent phases, supporting replication, governance improvement, and long-term scalability across 3DxVERSE pilots.

2. SUSTAINABLE MOBILITY AND ITS POLICY INTEGRATION USE-CASE (HAMBURG, ARUBA & TIMISOARA PILOTS)

2.1. Context and Scope of Mobility Pilots

The mobility pilots demonstrate how a Local Digital Twin (LDT) can act as an interoperable, data-driven platform for sustainable mobility management within a complex urban environment. As part of Hamburg's Integrated ITS Policy and Digital Mobility Strategy, the pilots connect traffic and logistics flows across the city areas to reduce congestion, lower CO₂ emissions, and enhance transparency in decision-making for public authorities and stakeholders.

Building on the conceptual foundations from deliverable D6.2 and the technical framework from deliverable D7.3, the Hamburg, Aruba and Timisoara pilots operationalize these concepts through historical data and later with semi-live integration, simulation, and participatory governance. They extend previous large-scale initiatives such as 5G-LOGINNOV and the TAVF (Testfeld Automatisiertes und Vernetztes Fahren) autonomous driving test track, aligning with Hamburg's long-term objective to implement the ITS Policy Act 2030.

The scope of the Hamburg pilot therefore focuses on four interlinked ideas:

1. Reducing congestion and travel times through dynamic and data-informed traffic management,
2. Monitoring and mitigating traffic-related CO₂ and pollutant emissions using harmonized LCMM data model and supported by historic FCD data model,
3. Supporting multimodal, low-carbon mobility planning through predictive and what-if simulations and interoperability with the European mobility data space, and,
4. Ensuring transparency and collaboration via stakeholder-facing dashboards that provide shared situational awareness for decision-makers, mobility authorities, and infrastructure operators.

The pilot's methodology and outcomes will be cross-referenced with the other mobility pilots such as Timisoara, which applies the same LCMM data structure to live fleet data from Uber and Continental, and Aruba, thereby demonstrating cross-border interoperability, scalability, and replicability of the 3DxVERSE Digital Twin framework.

2.2. Objectives of Mobility Pilots

The Hamburg, Aruba and Timișoara mobility pilots jointly represent the first implementation wave of the 3DxVERSE Mobility Local Digital Twin (LDT). This version of Deliverable D8.4 establishes the implementation framework that will guide how the available datasets are connected, harmonised, and prepared for integration into the 3DxVERSE Interoperable Digital Twin Testbed. The purpose is to ensure that, once activated, LDTs can provide valuable insights to stakeholders, supporting evidence-based urban planning, mobility policy, and decarbonisation strategies.

At this stage, the focus is on structuring the practical steps and data workflows required to operationalize the Local Digital Twin (LDT) once all data streams are integrated into the testbed, given that data foundation is already in place.

The LCMM (Low Carbon Mobility Management) dataset, that is collected from real trips through connected mobile devices, forms the core and most consistent source of data. This is supported by additional datasets that will enhance the accuracy and context of the Digital Twin once integrated:

- Floating Car Data (FCD): to complement LCMM with broader fleet and traffic movement insights.
- Maintenance & Construction site data: to capture temporary disruptions or bottlenecks affecting congestion and emissions.
- SPaT/MAP (Time-to-Green / GLOSA): to enable real-time analysis of traffic signal performance and eco-driving conditions.
- Environmental and mobility platform data: where available, from local authorities or public APIs, providing additional layers of validation and visualisation.

The implementation framework defined here will allow these data sources to be connected, validated, and synchronised through a shared interoperability layer compliant with ISO 23795-1 and other standards defined under WP5.

2.3. Use Cases of Mobility Pilots

UC 1 – Connected and Automated Mobility using advanced ITS

This use case prepares the integration of CCAM, ITS, FCD, and traffic-signal systems data into the LDT environment. At this stage, the goal is to construct an analytical layer that describes traffic interactions between vehicles and infrastructure based on existing LCMM and historical FCD records with the aim to analyze traffic dynamics, detect congestion, and identify emission hotspots using interactive local Digital Twin. The goal is to minimise stop-and-go traffic, improve travel-time reliability, and reduce idling emissions. This UC focuses on optimizing the interaction between vehicles and traffic infrastructure. By leveraging data from the TAVF testbed and the Mobility Data Space, the CCAM component tests innovative solutions such as adaptive signal control, time-to-green (GLOSA) services, and eco-routing algorithms.

The current goal for this UC is to build the static baseline of the CCAM–ITS environment and validate the interoperability of available datasets for future semi-dynamic operations.

UC2 – Holistic Traffic and Carbon Monitoring

This use case establishes the environmental analytics layer of the LDT, focusing on quantifying transport-related emissions. The LCMM dataset provides the primary emission and efficiency indicators, while FCD and maintenance & construction-sites data add additional spatial and temporal context. Where available, archived SPaT/MAP records help assess correlations between signal timing and emission peaks.

Outputs from this stage will include energy-labelled road segments and emission density maps that describe past mobility behaviour. These results will serve as a benchmark for the semi-live LDT, which will later update emission indicators at regular intervals.

The current implementation goal is to Integrate and process historical LCMM-based mobility data to generate carbon-intensity and congestion maps that can be periodically refreshed in the next phase.

This use case supports evidence-based planning by allowing authorities to prioritise interventions on the most polluting routes.

UC3 – Data-Driven Traffic Management and Decision Support

The third use case focuses on building the simulation and decision-support environment based on the current datasets. By combining the mobility and environmental data prepared in the previous use cases, the LDT will allow authorities and stakeholders to explore what-if scenarios, such as congestion episodes, construction detours, or policy simulations.

The implementation phase will design and test dashboard prototypes that visualise congestion patterns, CO₂ intensity, and travel-time metrics derived from LCMM and supportive datasets.

The current implementation goal for this UC is to create a simulation-ready environment using validated historical data, ensuring that interfaces and workflows are ready for new data and semi-dynamic use in the next project stage.

Through the LDT, city planners can test scenarios such as new low-emission zones, bridge closures, or bus-priority schemes, and immediately assess their effects on congestion, emissions, and travel time.

Dashboards and open interfaces connect authorities directly with citizens, promoting transparency and co-creation in mobility planning.

2.4. Pilots Implementation Framework

The implementation framework defines how the mobility pilots in Hamburg, Timișoara and Aruba will operationalise the 3DxVERSE concept by translating design principles and data models from D6.2 and technical components from D7.3 into an executable structure. This framework provides the blueprint for transforming validated data sources and interoperability specifications into a functioning Local Digital Twin (LDT) ecosystem that supports analytical processing, simulation, and stakeholder decision-making.

2.4.1. Data Architecture and Sources

The data architecture for the mobility pilots integrates both homogeneous and heterogeneous datasets into a unified, standards-based environment designed to support the Local Digital Twin (LDT) for sustainable mobility management and the decarbonization of road transport.

The architecture follows the cross-work-package logic established in WP6 (Use Cases: Mobility and Airports), WP7 (Interoperable Digital Twin Testbed), and WP5 (Security, Trust and Governance of Digital Twins), while applying the governance and stakeholder-engagement principles.

The data architecture structure ensures interoperability, provenance, and governance consistency across pilot sites, enabling gradual transition from data integration to analytical exploitation within the 3DxVERSE ecosystem.

At the core of this architecture are two primary and complementary data sources: the Low Carbon Mobility Management (LCMM) application and Floating Car Data (FCD) feeds. Together, they establish the empirical foundation for modelling mobility patterns, traffic flow dynamics, and carbon intensity within the pilots' operational areas.

The Low Carbon Mobility Management (LCMM) data:

LCMM application, developed under Deutsche Telekom's Green Magenta program, functions as an intelligent probe-vehicle platform that records trip-level mobility, energy, and emission data via embedded smartphone sensors such as GPS and optional vehicle interfaces. Each trip entry includes detailed telemetry such as duration, distance, average and instantaneous speeds, and fuel consumption, complemented by derived indicators such as the Acceleration Performance Index (API), Energy Performance Index (EPI), aerodynamic and grade-work components, and percentage standstill time. These variables collectively describe the vehicle's energy conversion efficiency and are essential for modelling carbon intensity and operational performance within the Local Digital Twin (LDT).

The LCMM system automatically converts these sensor readings into energy-use (MJ) and CO₂-equivalent (kg) metrics, distinguishing between total and saved emissions for each journey. For example, a typical recorded trip of approximately 49.8 km and 7 h 45 min duration produces a CO₂

emission of 15.5 kg with 7.6 kg saved through eco-driving optimisation. Energy breakdowns follow the ISO 23795-1 “Probe Vehicle / Floating Car Data Standard”, ensuring consistency in sampling frequency, positional accuracy, and timestamp synchronisation.

The app disaggregates the trip into analytical categories—aero cycle, roll work, grade work, standstill work, and acceleration cycle—enabling identification of where inefficiencies occur and how driver behaviour or infrastructure conditions contribute to excess fuel consumption.

By conforming to ISO 23795-1, LCMM data achieve interoperability with fleet-based Floating Car Data (FCD) systems, allowing direct integration into the 3DxVERSE mobility data pipeline. Each LCMM record is geotagged, timestamped, and indexed, enabling spatio-temporal aggregation and correlation with complementary datasets such as FCD, SPaT/MAP (time-to-green) signals, and construction-site information. This comprehensive trip-level profiling transforms LCMM from a behavioural monitoring tool into a scientifically validated emissions-assessment framework, serving as the empirical backbone of the 3DxVERSE Local Digital Twin and a key enabler of data-driven decarbonisation strategies.

Details	Map	Speed Profile	Altitude Profile	Emission Profile	Way Profil	Info
Vehicle dt048		Group name 3DxVerse.	Start time 04.11.2025, 15:44	End time 04.11.2025, 23:30		
Duration 07:45:21		Distance 49,8 km	Speed 6,4 km/ h	Fuel Consumption 11,7 l/ 100km		
CO2 Emission (in total/saved) 15,5 kg / -7,6 kg		Zero fuel distance 6.704 m	Standstill time 05:46:24	ACC Cycle 99,5 %		
Aero Cycle 60,7 %		Percentage Standstill Cycle 17,9 %	Percentage Work Cycle 67,2 %	Energy Performance Index (EPI) 1,9 l/ 100km*t		
Acceleration Performance Index (API) 4,4 kWh/ 100km*t		WLTP Cycle low/med/high/extra 63 / 34 / 3 / - %	Totalwork 114,2 MJ	AccWork 27,7 MJ (24 %)		
AeroWork 9,3 MJ (8 %)		Standstill work 1,3 MJ (1 %)	RollWork 14,7 MJ (13 %)	GradeWork 61,2 MJ (54 %)		
Cross section area 5.5 m²		Efficiency 55 %	Fuel emissions-factor 2.664 kg/l	Fuel type Diesel		

Figure 3: Snapshot from the LCMM database

The LCMM app has been officially recognised in the UNFCCC’s (The United Nations Framework Convention on Climate Change) “Momentum for Change” initiative under the theme “Low Carbon Mobility Management – China and Germany”. According to the UNFCCC database, the app has achieved over 800,000 km of trips logged in Germany, with an average fuel-consumption reduction of 9%, and a payback period for users between 6 and 9 months (UNFCCC, n.d.). This recognition is a strong indicator of the app’s value and scalability in supporting decarbonisation in the mobility sector. Within the context of the 3DxVERSE mobility pilots, LCMM therefore serves as a technically validated, internationally recognised source of driving-behaviour and emission-deviation data. Its integration into the LDT provides an evidence-based foundation for modelling driving efficiency, quantifying CO₂-equivalent deviation, and supporting stakeholder decision-making for sustainable mobility interventions.

The Floating Car Data (FCD):

FCD streams are continuously collected from logistics, taxi, and ride-sharing fleets operating in the Hamburg metropolitan region and, where applicable, in other mobility pilot corridors. These feeds capture vehicle position, velocity, acceleration, and estimated energy consumption per kilometre.

Because both FCD and LCMM adopt ISO 23795-1 structures, they can be seamlessly harmonised within the LDT’s operational layer, creating a composite dataset that links individual driving behaviour with fleet-level performance. This integrated view provides the analytical foundation for CCAM simulations and network-wide emission modelling.

Auxiliary Data Streams:

Beyond these primary layers, several auxiliary data streams enhance the model's contextual accuracy:

- Maintenance and construction-site updates provide spatial and temporal markers for roadworks, diversions, and capacity constraints.
- Environmental and meteorological data including NO_x, SO_x, and PM_{2.5} concentrations, as well as temperature, humidity, and wind patterns, offer environmental baselines for correlating mobility and air-quality conditions.
- Port and logistics data from the Hamburg Port Authority (HPA) supply information on truck movements, gate waiting times, and route congestion, linking freight and passenger mobility analyses.

Each dataset from the above three data sources is timestamped, georeferenced, and indexed upon ingestion, maintaining data lineage and traceability throughout the analytical workflow. Data ingestion and harmonisation occur within the Interoperable Digital Twin Testbed, which provides a secure pipeline for extraction, transformation, validation, and loading (ETL). Validation routines verify compliance with ISO 23795-1 field constraints, positional accuracy, and timestamp integrity before harmonisation into spatio-temporal layers aggregated at a certain time intervals. These harmonised layers are stored in cloud environments that are compliant with GDPR rules, ensuring data integrity, retention, and controlled accessibility.

Security and governance are enforced through a multilayered framework integrating the Trust Framework for authentication and access control. Data lifecycle management adheres to FAIR principles (Findable, Accessible, Interoperable, Reusable) and to the EU Data Governance Act (DGA).

To maintain compliance with EU-level cybersecurity policy, pilots implement the ENISA Interoperable EU Risk Management Toolbox (ENISA, 2023), ensuring uniform threat categorisation, asset classification, and impact assessment across pilot sites.

Finally, the entire data architecture embeds security-and-privacy-by-design and data minimisation principles. Personal identifiers within LCMM are pseudonymised at source; trip-level summaries replace raw trajectories; and all analytical outputs are disseminated through controlled stakeholder dashboards or public-facing interfaces consistent with WP8's stakeholders-engagement objectives. Through this combination of LCMM data, professional fleet telemetry, and institutional data layers, the mobility pilots establish a robust, standardised, and GDPR-compliant data foundation for advancing evidence-based, low-carbon mobility planning within the 3DxVERSE ecosystem.

2.4.2. Stakeholders & Partners

The implementation of the mobility pilots relies on a multi-actor governance framework that connects public authorities, research institutions, industry partners, and citizens within a single interoperable ecosystem. This arrangement reflects the 3DxVERSE principle of federated collaboration, where every partner contributes to specific competences across the data, technical, governance, and engagement layers of the Local Digital Twin (LDT). The stakeholders and partners for the mobility pilots are:

ERTICO:

At the strategic level, ERTICO acts as the project coordinator, ensuring alignment across work packages, consistency of pilot methodologies, and compliance with the European Commission's innovation and interoperability frameworks. ERTICO supervises reporting, dissemination, and cross-pilot knowledge transfer between the four 3DxVERSE sites, Hamburg, Aruba, Almelo, and Timișoara, so that outputs generated in one environment can be replicated in another. ERTICO also oversees adherence to the Local Digital Twin Toolbox and CitiVerse reference architecture, guaranteeing technical and methodological traceability across the consortium.

ILABS:

This partner serves as the lead for Trust, Security, and DevSecOps, operationalising the framework described in D5.1. It embeds privacy-and-security-by-design principles throughout the data lifecycle and supervises risk-management using the ENISA Interoperable EU Risk Management Toolbox (ENISA, 2023). ILABS defines the DevSecOps pipeline for the pilots, manages continuous integration and conformance testing of the iSHARE-based authentication workflows, and provides templates for Data Protection Impact Assessments (DPIA) and Privacy Impact Assessments (PIA). Within the implementation stage, it monitors compliance against the ISO 23795-1 data-quality requirements and contributes to the “lessons learned” synthesis on trust and governance for cross-pilot scalability.

T-Systems and Deutsche Telekom:

They act as dual technology and data providers. They jointly developed and maintain the Low Carbon Mobility Management (LCMM) application under the Green Magenta initiative, delivering driver-sourced mobility data that conform to ISO 23795-1. In the Hamburg pilot, T-Systems is a support partner which ensures the technical integration of LCMM data into the LDT ingestion pipeline, provides backend analytics, and coordinates with other partners such as Ambrosys on pseudonymisation and GDPR-compliance controls. Beyond data provision, T-Systems collaborates with the City of Hamburg’s transport authorities to test eco-routing, time-to-green (GLOSA), and Connected and Automated Mobility (CCAM) services, generating empirical evidence for decarbonisation KPIs and decision-support models.

Hamburg Port Authority (HPA) and Hamburg City Authority:

They act as a co-end-user and operational partner, focusing on port-related logistics and multimodal traffic coordination. It provides access to infrastructure data, supervises integration with the port’s mobility systems, and validates Connected and Automated Mobility (CCAM) simulations against real operational benchmarks. Together they ensure that LDT insights feed directly into local traffic management, sustainability, and infrastructure investment planning.

ITS Mobility GmbH:

ITS Hamburg acts as the technical integrator for mobility data, responsible for harmonising FCD and LCMM feeds, performing data-quality assurance, and maintaining the operational testbed. It developed the ingestion and validation architecture used by Hamburg and during the pilot operation phase, it will continue to calibrate traffic-flow and emission models while supporting KPI validation for energy efficiency and congestion reduction.

ESRI:

ESRI provides the geospatial backbone of the 3DxVERSE Interoperable Digital Twin Testbed. Through ArcGIS-based data hubs, APIs, and 3D-scene hosting, ESRI enables integration with European spatial-data standards and the Commission’s Local Digital Twin Toolbox. ESRI’s environment also underpins public-facing dashboards for transparency and replicability, ensuring that visual analytics produced by the pilots remain consistent with open geospatial interoperability frameworks.

The Hague University of Applied Sciences (THUAS):

THUAS leads stakeholders’ engagement under WP8, contributing academic and methodological expertise in participatory design. THUAS will conduct co-creation workshops, supports communication with groups, and ensures that visualisations and dashboards are understandable to all users.

City of Hamburg’s Ministry of Transport and Mobility Transition (BVM):

The BVM serves as the lead public authority and primary end-user of the Hamburg pilot. It ensures alignment between the LDT outcomes and the city’s ITS 2030 strategy, mobility transition policies, and climate objectives. BVM oversees regulatory compliance for traffic and emissions data use, validates model outputs, and integrates pilot results into urban-planning and mobility-policy frameworks.

Timișoara Municipality and Local Mobility Authorities:

The Municipality of Timișoara and its local mobility authorities function as the end-users and implementing bodies for the Romanian pilot. They supply fleet, public-transport, and traffic datasets, manage interoperability with LCMM data, and integrate the LDT results into municipal mobility strategies. Their participation demonstrates the adaptability of the 3DxVERSE framework to a mid-sized European city and ensures the pilot’s policy relevance, operational uptake, and future scalability.

This multi-layered partnership reflects best practice in digital-twin governance, as emphasised by Ehwi et al. (2023). Early role definition, data-sharing clarity, and inclusive participation reduce duplication of effort, increase system transparency, and strengthen cross-sectoral ownership. In the Hamburg, Aruba and Timișoara pilots, stakeholder collaboration spans all phases of the lifecycle:

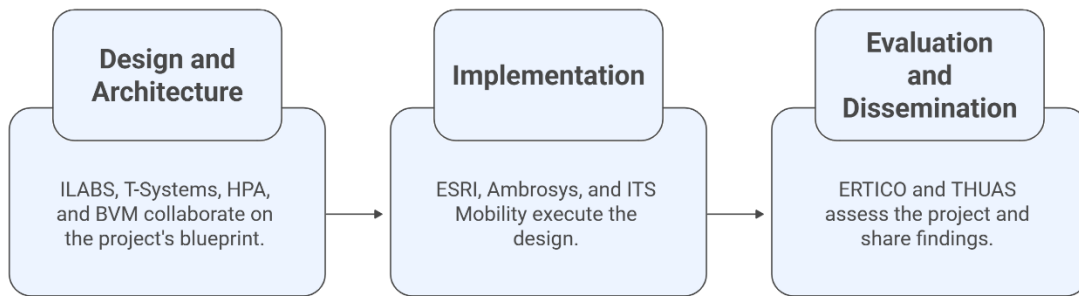


Figure 4: Stakeholders' collaboration across Hamburg LDT lifecycle

Collectively, these actors embody the governance model envisioned for 3DxVERSE: an interoperable, trust-driven ecosystem in which industry, academia, public authorities, and citizens co-create sustainable and replicable mobility solutions.

Table 2: Stakeholders and Partners Mapping for the Mobility Pilots

Stakeholder / Partner	Primary Role	Main Contribution / Responsibilities
ERTICO	Project Coordinator & Consortium Manager	Ensures cross-WP alignment, reporting, and EC liaison; facilitates interoperability & knowledge transfer among all pilots.
ILABS	Trust, Security & DevSecOps Lead	Implements WP5 Trust Framework; manages DevSecOps pipeline; oversees GDPR compliance & risk assessment using ENISA Toolbox.
T-Systems / Deutsche Telekom	Technology & Data Provider	Develops and maintains LCMM platform (Green Magenta); provides ISO 23795-1 mobility data; supports eco-routing & CCAM testing; delivers backend analytics.
Ambrosys GmbH	LDT Architect & Technical Lead	Designs and deploys LDT architecture; integrates open source & commercial frameworks; supervises data ingestion and simulation modules.
ESRI	Geospatial Platform Provider	Provides ArcGIS-based data hubs & 3D hosting; ensures alignment with EU LDT

		Toolbox standards; enables public dashboards for transparency.
ITS Mobility GmbH	Mobility Data Integrator & Testbed Operator	Harmonises FCD and LCMM feeds; performs data-quality monitoring; supports KPI validation and simulation testing within the LDT.
City of Hamburg – Ministry of Transport and Mobility Transition (BVM)	Public Governance & Policy Coordinator	Provides regulatory oversight; aligns pilot with ITS 2030 strategy; validates LDT outputs and integrates results into urban-mobility planning.
Hamburg Port Authority (HPA)	Port Mobility Stakeholder & Data Provider	Supplies logistics and traffic datasets; validates CCAM use cases; coordinates integration with port infrastructure and ITS ecosystem.
Timișoara Municipality & Local Mobility Authorities	Local Implementation Partner (Romanian Pilot)	Provides fleet and traffic data; ensures interoperability with LCMM datasets; validates LDT integration within municipal mobility strategies.
The Hague University of Applied Sciences (THUAS)	Citizen Engagement & Evaluation Partner	Leads co-creation workshops and participatory evaluation; analyses stakeholder feedback to improve usability and trust in LDT outputs.

2.4.3. Data Models and Simulations

The mobility pilots in Hamburg, Aruba, and Timișoara constitute the analytical backbone of the 3DxVERSE project's Local Digital Twin (LDT) initiative. They demonstrate how harmonised data models and simulation workflows can translate raw mobility and environmental data into operational intelligence for urban decarbonisation and transport optimisation.

Hamburg Pilot:

The Hamburg Local Digital Twin integrates advanced data-modelling and simulation capabilities to analyse the interrelations between mobility flows, emission profiles, and infrastructural constraints in a large metropolitan and port environment. The model architecture is developed and orchestrated by Ambrosys GmbH in collaboration with ESRI, ITS Mobility, and local authorities (BVM and HPA). The analytical environment runs within the IDTT, which combines ESRI ArcGIS for geospatial management with Cesium-based open-source engines for temporal visualisation and 3D rendering. This hybrid stack ensures interoperability with the EU Local Digital Twin Toolbox and supports future scalability to other pilot sites.

The data models are built primarily on ISO 23795-1-compliant LCMM and FCD sources. These datasets record trip-level mobility and energy information, including speed, distance, acceleration, and CO₂-equivalent estimates, collected from over 100,000 trips logged during Hamburg's ITS World Congress (2021) and 5G-LOGINNOV trials. They are complemented by:

- Maintenance and Construction-site data identifying temporary disruptions and their effect on congestion.
- Port-logistics datasets from the Hamburg Port Authority (HPA), including truck arrival times, gate-waiting durations, and route congestion.

- Environmental and meteorological feeds containing air-quality and weather variables; and
- SPaT/MAP (Time-to-Green / GLOSA) data used to model adaptive signalisation effects on eco-driving.

Simulation models use WLTP (Worldwide Harmonised Light Vehicle Test Procedure) parameters as reference curves to measure deviations between theoretical and real-world driving efficiency. All data are harmonised through standardised ETL pipelines and validated under the Trust Framework and the Risk Management Toolbox (ENISA, 2023).

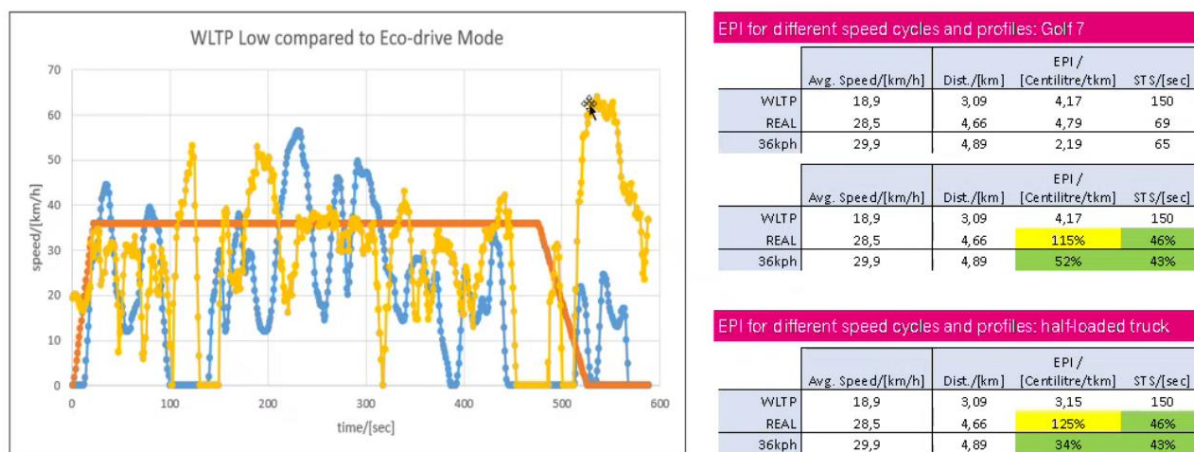


Figure 5: Snapshot from LCMM simulation model (WLTP vs. Real)

The Hamburg simulation framework consists of two interlinked model families:

1. **Mobility and Emission Models:** Derived from LCMM, FCD, and processed construction and port datasets, these models quantify energy use and emissions per road segment and time interval. They produce energy-labelled corridors showing the combined effects of driving behaviour, road works, and freight activity on CO₂ and NO_x intensity.
2. **Traffic-Flow and Eco-Routing Models:** Executed through Ambrosys's orchestration engine, these simulations integrate CCAM, FCD, LCMM, and SPaT/MAP data to evaluate adaptive-signal strategies, travel-time reliability, and eco-driving performance. Pre-processed construction site information informs network capacity and detour parameters used in the simulations.

Outputs are visualised through the Mobility Twin Hub, providing interactive dashboards for mobility authorities (BVM, HPA) and drivers. These tools support scenario testing and policy evaluation by displaying congestion propagation, emission hotspots, and potential efficiency gains from eco-routing or construction-planning measures. This environment also serves as the reference model for the replication pilot in Timișoara, Aruba and any other future pilots.

Aruba and Timișoara Pilots:

The Aruba and Timișoara LDT replicates the Hamburg framework within small to medium sized cities to demonstrate transferability and localisation. The mobility operators collaborate with ERTICO, Ambrosys, ESRI, ITS, and ILABS to deploy the shared 3DxVERSE data model and simulation workflows.

Timișoara's datasets include LCMM trips, fleet and ride-sharing data (Uber, Continental), and air-quality observations. For Aruba, data from airport suppliers' trucks and airport taxis will be collected from LCMM app. Construction-related data could be incorporated as contextual modifiers to support emission and traffic-flow analyses, mirroring Hamburg's integrated approach. This pilot validates the 3DxVERSE methodology in a semi-live data environment and demonstrates interoperability across different regulatory and infrastructural settings.

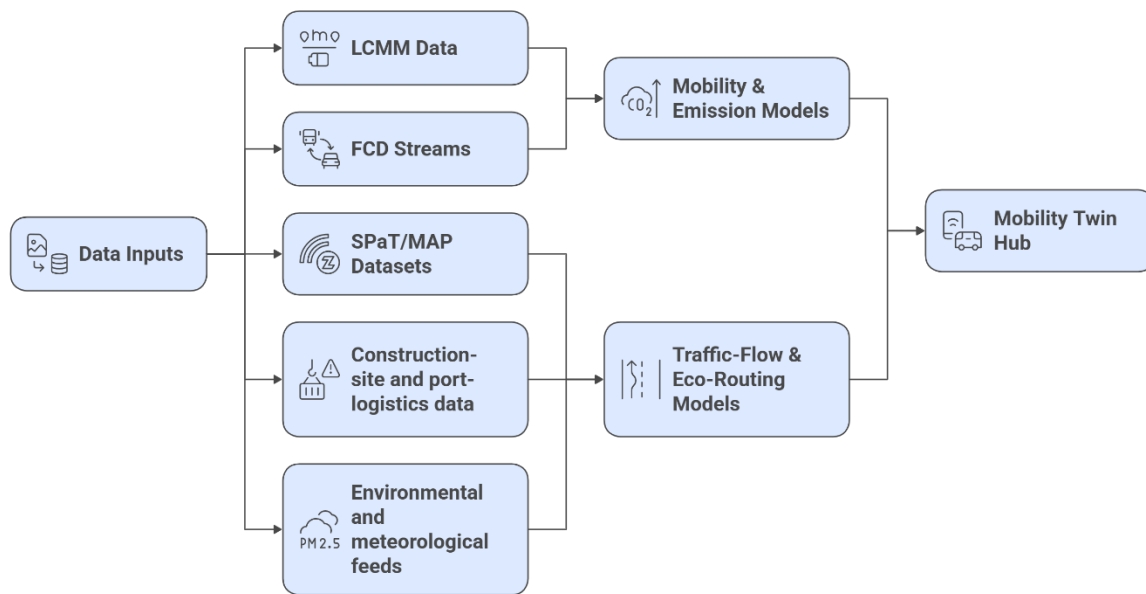


Figure 6: Data Flow and Modelling Architecture of the Mobility Pilots

2.4.4. Implementation Stages

The implementation of the mobility pilots follows a phased roadmap designed to ensure technical maturity, governance compliance, and replicability across different city environments. This progression allows the 3DxVERSE consortium to evolve from validated static analysis to semi-dynamic decision support and ultimately to a harmonised, cross-pilot reference model.

Stage 1 – Static Local Digital Twin

The first stage establishes a Static Local Digital Twin (LDT) as the foundational analytical environment for the mainly Hamburg pilot and the pilots of Aruba and Timișoara. At this level, datasets are historical, pre-processed, and harmonised to create a stable reference for model calibration, validation, and stakeholder familiarisation. Core datasets include LCMM, FCD, SPaT/MAP, and construction-site and port-logistics data. All information is processed through standardised ETL pipelines within the Interoperable Digital Twin Testbed (IDTT), aligned with ISO relevant standards such as ISO 23795-1.

This stage is primarily designed for technical reliability and compliance testing. WP5 validates security and privacy controls using the Trust Framework and the Risk Management Toolbox (2023). Ambrosys GmbH leads simulation model calibration, ESRI builds the 3D digital twin visualization, while BVM and HPA verify data-sharing and interoperability agreements. Outputs visualised in the Mobility Twin Hub allow authorities to analyse congestion and emissions baselines under full GDPR and data-provenance assurance.

The static LDT therefore functions as a low-risk, fully auditable baseline where models, trust mechanisms, and governance workflows are validated before dynamic data integration.

Stage 2 – Semi-Dynamic Local Digital Twin

The second stage advances to a Semi-Dynamic LDT, integrating both historical and semi-real-time datasets to enable temporal simulation and adaptive scenario testing. Validated data structures from Stage 1 remain in place, but new ingestion routines allow periodic or batch updates from LCMM, FCD, and SPaT/MAP sources, supplemented by refreshed environmental and infrastructure data.

In Hamburg, this configuration enables the replay of realistic operational conditions such as adaptive-signal strategies, eco-routing interventions, or construction-related detours by combining time-stamped

LCMM and FCD traces with current contextual data. In Aruba and Timișoara, equivalent semi-dynamic integration uses live fleet and municipal datasets to confirm interoperability and transferability of the Hamburg model.

The semi-dynamic twin functions as an interactive decision-support platform. Stakeholders and end-users can execute “what-if” analyses, assess emission-reduction options, and evaluate mobility policies before implementation. Iterative calibration and KPI validation are managed by different partners, with feedback collected through WP8 evaluation workshops.

All data flows remain protected under the DevSecOps pipeline and the risk-management framework, ensuring consistent trust and compliance as new temporal layers are introduced.

Stage 3 – Scale-Out and Replication

The third stage expands beyond pilot-specific operation to achieve cross-pilot replication and European interoperability. This Scale-Out and Replication Stage transforms the Hamburg, Aruba, and Timișoara twins into reusable reference models for the broader CitiVerse mobility ecosystem and all other new pilots that onboard the project.

At this level, emphasis shifts from model execution to standardisation, documentation, and federated integration following the 3DxVERSE’s deliverables for interoperability and data governance. The scale-out stage therefore establishes 3DxVERSE as a replicable architecture, ensuring that the digital-twin methodologies, models, and trust frameworks demonstrated in those pilots can be adopted by additional European municipalities and future Horizon Europe initiatives.

2.4.5. KPI and Evaluation Framework

The KPI and evaluation framework defines how the performance and impact of the mobility pilots will be measured, validated, and continuously improved throughout all implementation stages of the Local Digital Twin (LDT). This framework draws on the indicators defined in the deliverable D6.2 and operationalises them through the 3DxVERSE Metrics Register, which consolidates measurable parameters across all pilots and work packages. It ensures that pilot progress can be tracked quantitatively while maintaining interoperability and comparability across the wider CitiVerse ecosystem.

The KPI system serves four complementary objectives:

1. Effectiveness Measurement – quantify environmental, operational, and social benefits resulting from pilot deployment.
2. Performance Monitoring – assess progress across the three implementation stages (Static → Semi-Dynamic → Scale-Out).
3. Adaptive Management – provides a data-driven feedback loop for continuous improvement of models and data workflows.
4. Cross-Pilot Benchmarking – enable alignment with other pilots through harmonised KPI schemas and NGSI-LD-compliant data exchange.

Table 3: KPI Framework by Use Case

Use Case	Objective	KPI / Metric	Primary Data Source(s)	Baseline (Static LDT)	Target	Evaluation Frequency
UC1 – Connected and Automated Mobility	Reduce CO ₂ emissions and travel time through connected	• CO ₂ emissions per vehicle-km (g CO ₂ e/km)	LCMM app; FCD streams;	2023 baseline from LCMM & FCD (Static LDT)	≥ 10 % CO ₂ reduction vs baseline;	Quarterly

(Advanced ITS)	mobility and time-to-green optimisation.	<ul style="list-style-type: none"> • Average idle time at signals (s) • Average travel time per corridor (min) • Share of energy-labelled street segments (%) 	SPaT/MAP data; BVM/HPA traffic datasets		<ul style="list-style-type: none"> ≥ 15 % idle-time reduction; ≥ 10 % travel-time improvement 	
UC2 – Holistic Traffic and Carbon Monitoring	Map and monitor energy consumption and emissions using harmonised LCMM and FCD data.	<ul style="list-style-type: none"> • Energy-labelled road coverage (%) • CO₂ emissions visualised in LDT (t/day) • PM₂₋₅ reduction (%) 	LCMM app; HPA GIS layers; ESRI LDT dashboards	2023 static emission baseline map	<ul style="list-style-type: none"> ≥ 10 % increase in energy-labelled coverage; ≥ 5 % CO₂ decrease; ≥ 3 % PM₂₋₅ reduction 	Semi-annual
UC3 – Data-Driven Mobility Policy Simulation and Evaluation	Assess decarbonisation impact of measures such as eco-routing, park-and-ride, or CCAM strategies.	<ul style="list-style-type: none"> • CO₂ reduction vs baseline (%) • Delay hours per corridor per day • Number of policy scenarios evaluated in LDT • Decision-maker satisfaction score (%) 	LCMM + FCD data; Ambrosys scenario engine; BVM/HPA policy datasets	2023 static LDT results	<ul style="list-style-type: none"> ≥ 10 % CO₂ reduction; ≥ 15 % decrease in delay hours; ≥ 70 % positive authority feedback 	Bi-annual
Cross-Pilot Alignment	Establish replicable KPI methodology and interoperability.	<ul style="list-style-type: none"> • Standardised KPI schema • API endpoints for KPI exchange (#) • Number of shared indicators across pilots (#) 	3DxVERSE KPI Register; WP7 APIs; WP5 Trust Registry	Hamburg KPI definitions (M24)	KPI framework adopted by ≥ 2 additional pilots	Annual

Performance evaluation is organised across three complementary levels to ensure coherence between technical accuracy, policy relevance, and project accountability:

- **Technical Review:** This level assesses model accuracy, data-flow consistency, and the robustness of simulation algorithms.
- **Policy Review:** This level focuses on interpreting KPIs in the context of mobility, congestion, and emission-reduction objectives.
- **Consortium Review:** This level consolidates KPI results for cross-pilot benchmarking, synthesis of findings, and reporting to the European Commission.

Each review cycle produces formal evaluation notes that are archived in the project's quality-assurance environment, ensuring traceability and enabling longitudinal performance comparison across implementation stages.

To maintain continuous improvement, KPI outcomes are directly linked to the model-refinement process illustrated in Figure 7. Whenever a measured indicator diverges from its defined target, for instance, if observed CO₂ reduction falls below the 10 percent benchmark, the feedback mechanism initiates corrective actions, including re-assessment of data-ingestion frequency and sensor calibration, adjustment of model parameters, and/or review and refinement of policy scenarios in cooperation with local authorities.

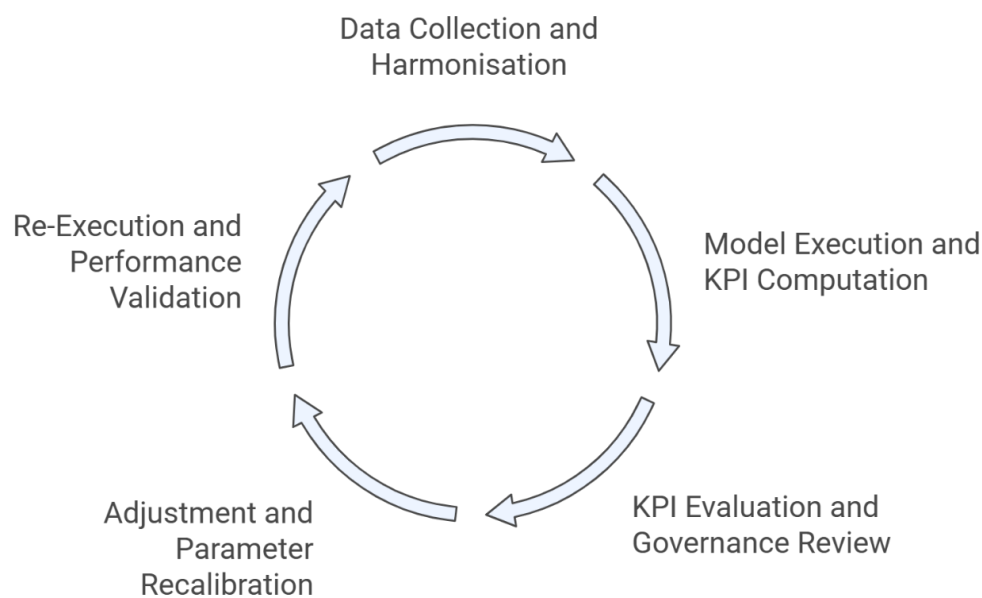


Figure 7: KPI Feedback and Continuous Improvement Loop

This structure ensures that lessons learned from each simulation cycle directly inform subsequent iterations, creating a self-learning digital-twin ecosystem. By integrating quantitative KPI results into iterative model refinement, the feedback loop guarantees that the pilots' analytical performance continuously converges toward the operational goals of efficiency, decarbonisation, and stakeholder trust. This iterative feedback cycle enables evidence-driven optimisation, ensuring that analytical precision and operational effectiveness improve with each subsequent implementation wave.

The KPI and evaluation framework extends beyond performance measurement, it serves as a mechanism for governance validation, institutional learning, and stakeholder trust-building. By translating analytical results into quantifiable indicators, the framework provides policy-relevant evidence to decision-makers, enabling informed mobility planning and investment decisions.

Furthermore, the transparent and iterative structure of KPI evaluation supports collective accountability among partners. This approach embodies the human-centred, evidence-based governance model at the core of 3DxVERSE Work Package 8, ensuring that LDT’s deliver demonstrable public value and enduring impact within the CitiVerse framework.

2.5. Governance and Interoperability Across Mobility Pilots

The governance model that underpins the 3DxVERSE mobility pilots in Hamburg, Aruba and, Timișoara is built directly on the Digital Twin and AI Trust Framework described in Deliverable D5.1. This framework defines governance as a structured set of rules, roles, and processes that enable trusted, secure, and interoperable collaboration across different digital-twin ecosystems. It integrates the principles of EU data sovereignty, interoperability, trust, and accountability, ensuring that digital twins operate transparently and consistently across cities and domains.

The D5.1 model identifies four principal governance roles within the 3DxVERSE ecosystem, each essential to the lifecycle of a trustworthy digital-twin environment:

1. **Governance Authority:** The 3DxVERSE Programme Board, coordinated by ERTICO – ITS Europe, acts as the overarching Governance Authority. It defines strategic objectives, ensures legal and ethical compliance, and provides final oversight on interoperability, security, and trustworthiness. Locally, this function is mirrored by public authorities such as BVM (Hamburg), Timișoara Municipality, and the Aruba Ministry of Transport, which govern mobility policy, data-sharing agreements, and regulatory adherence in each pilot.
2. **Providers:** They are the technical and operational entities supplying data, algorithms, and infrastructure to the digital-twin ecosystem. This group includes ESRI, Ambrosys GmbH, ILABS, T-Systems / Deutsche Telekom, and ITS Mobility GmbH. They are responsible for developing and maintaining the LDT infrastructure, ensuring compliance with ISO 23795-1, NGSI-LD, and OASC MIMs, and guaranteeing interoperability across pilots. Under the Trust Framework, providers maintain operational integrity, access control, and provenance tracking.
3. **Consumers:** They are the institutional and professional end-users of the LDT. In the mobility pilots, these are primarily public mobility authorities, planning departments, traffic management agencies, and vehicles’ drivers. They consume validated insights, simulation outputs, and KPIs from the digital twin to inform mobility strategies, congestion management, environmental policies and driving patterns.
4. **Observers:** They ensure accountability and ethical compliance. They include THUAS, ILABS, and external regulatory or auditing bodies. Their function is to monitor risk, audit data flows, and evaluate adherence to trust, transparency, and ethical expectations.

In alignment with D5.1, all participants operate within five interconnected lifecycle stages that define the digital-twin governance process:

Table 4: Lifecycle Governance Process

Lifecycle Stage	Purpose	Outputs / Controls
Stage 0 – Pre-boarding / Registration	Assess eligibility, risk, and trustworthiness of participants.	Legal vetting, compliance pre-checks, registration in Trust Registry.

Stage 1 – Onboarding	Assign roles and define policies and permissions.	Role assignment, credential exchange, consent registration.
Stage 2 – Provisioning	Enable secure and authenticated data exchange between actors.	API provisioning, secure channels, SLA and DGA-compliant data contracts.
Stage 3 – Management	Operate and monitor the ecosystem, ensuring transparency and compliance.	Data provenance logging, KPI dashboards, ongoing risk assessment.
Stage 4 – Off-boarding	Manage participant exit, revoke credentials, and preserve data integrity.	Audit closure, risk residuals assessment, archival of governance records.

Governance interoperability between Hamburg, Aruba, and Timișoara is achieved by federating local governance structures under the D5.1 Trust Framework. This means each pilot maintains local autonomy but adheres to the same policy schema, identity model, and trust registry.

The trust framework is inherently scalable, allowing new pilots to join the ecosystem without redesigning the governance structure. By adhering to a unified trust framework, future city or sector pilots can seamlessly integrate by registering their roles within the existing governance tiers and lifecycle.

This approach turns governance itself into an interoperable asset: replicable, auditable, and compliant with EU data-space standards. It establishes the 3DxVERSE ecosystem as a federated network of trusted, ethical, and interoperable LDT's, capable of delivering sustainable, data-driven transformation across European and global smart-mobility domains.

2.6. LCMM Data Interoperability for Mobility Pilots

The Low Carbon Mobility Management (LCMM) framework provides a unified, carrier-agnostic data environment enabling the Hamburg, Timișoara, and Aruba pilots to collect, process, and compare mobility and emission data under a common standard. LCMM uses the sensors embedded in smartphones to record location, speed, and time directly from the device's Global Navigation Satellite System (GNSS), making data acquisition fully independent of the user's mobile operator. Differences between national telecom providers affect only data transmission, not the structure, accuracy, or frequency of measurement.

All LCMM datasets adhere to ISO 23795-1, which prescribes uniform data fields, positional accuracy, and timestamp integrity. This standardisation ensures that every trip, regardless of origin, is encoded through the same metadata structure and can be seamlessly integrated into the Interoperable Digital Twin Testbed. The data are harmonised through identical ETL pipelines and validated within the Trust Framework, guaranteeing provenance, traceability, and compliance with GDPR and the EU Data Governance Act.

A single computation method, anchored in the Worldwide Harmonised Light Vehicle Test Procedure (WLTP), converts recorded speed profiles into energy-consumption and CO₂-equivalent estimates. By referencing all measurements to the same WLTP baseline, LCMM delivers cross-comparable indicators such as energy-labelled corridors, CO₂ intensity, and idle-time metrics across different cities and use cases.

2.6.1. Some regulatory background to the role of LCMM in 3DxVerse

For road transport, the EN ISO 14083:2023 standard uses WLTP and RDE testing data (gCO₂/km) from vehicle registrations, multiplied by mileage, to calculate annual emissions. Regulation (EU) 2017/1151 mandates On-Board Diagnostics (OBU/PEMS) to anonymously monitor real fuel/carbon consumption, reporting annual WLTP deviations to the European Environment Agency EEA—fully GDPR-compliant.

Importantly, mandatory OBUs do not track real-time trip data (like geo-location or speed). For operational fleet management purposes, short-term carbon monitoring (e.g., daily/weekly), ISO 23795 comes into the game using nomadic devices (smartphones, IoT-devices) to provide real-time emissions data to change routes and/or driving behaviour.

In short:

- ISO 14083 → Annual average emissions (like climate research).
- ISO 23795 → Real-time trip data (like weather reports).

Thus, both ISO-standards use CAN-Bus data and WLTP deviations but serve different purposes. ERTICO was involved in publishing both ISO-standards and was the main ISO project initiator for ISO-23795 via Belgium standardization body NBN.

Finally, both standards are fully complementary and help decarbonizing road transport on different operational timeframes and management levels.

For ISO-14083, EU's new CountEmissionsEU regulation harmonizes carbon emission calculations across transport modes, reinforcing Europe's leadership under the "Fit for 55" initiative, [For further details](#).

As mentioned, for both ISO-Standards UN Regulation No.154 provides uniform provisions for the approval of light-duty vehicles regarding emissions of carbon dioxide and fuel consumption, and is closely linked to the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) and Real Driving Emissions (RDE) testing, which can involve OBU (On-Board Units) and PEMS for real-world measurement, annually for ISO-14083 and daily for ISO-23795. For the local digital twin (LDT) in 3DxVerse, this brings the %WLTP measured trip values to the key user inclusion of the living mobility community and environment. This is shown in Table 5: (%) -WLTP Vehicle Registration and measured for the registered fuel values of a volume mass market brand, the VW Polo, in Liter per 100km or (lph).

Table 5: (%) -WLTP Vehicle Registration and measured

WLTP MODE	LOW	Medium	HIGH	EXTRA-HIGH	AVERAGE
Registered	25%(7,2)	25%(5,5)	25%(5,1)	25%(6,1)	25% (5,8lph)
Measured (e.g.)	80%(7,2)	10%(5,5)	10%(5,1)	0%	(6,8lph)

To better understand the role of WLTP reference speed profiles, see Figure 8.

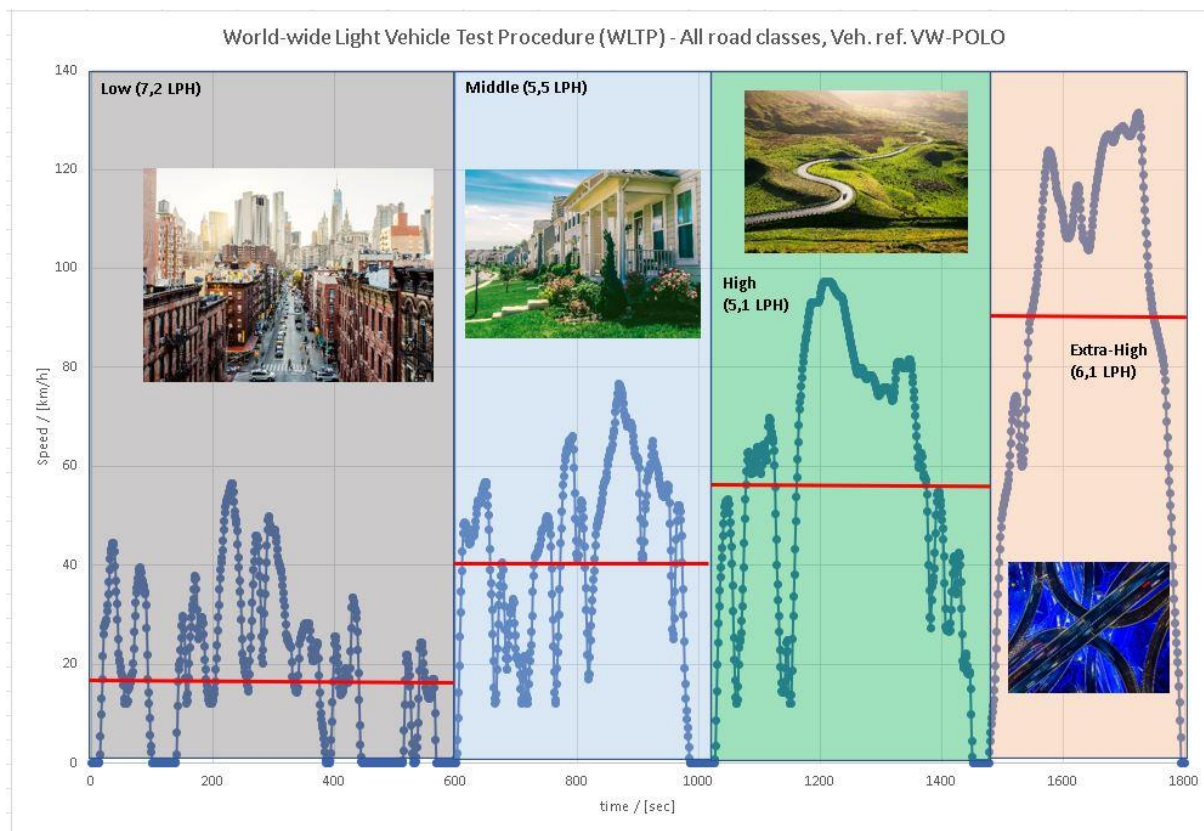


Figure 8: WLTP Speed Profile Road Classed References (Visual)

2.6.2. User Engagement in Hamburg, Timisoara and Aruba

This 3DxVerse project includes piloting digital twin applications with active citizen participation, aiming to transform airports, enhance airline operations, and foster innovative, sustainable living communities. Citizens are empowered through personalized tools and real-time data, enabling them to contribute to urban planning and smart community development. The goal is to evaluate real-world effectiveness, ensure citizen satisfaction, and build scalable, interoperable solutions through international collaboration and strong data governance.

For the mobility use case in Phase 1, this includes collecting (%) -WLTP relevant data, given the regulatory importance of these data sets. With the global coverage of GSM and GNSS, 3DxVerse could show in the first user inclusion phase of the project how interoperability could be achieved by individual drivers and fleet operators making use of the LCMM app, available in Android Playstore and iOS Appstore for public download and data collection.

Tables 6 and 7 show the data collected within the Hamburg pilot, in the time from May to August 2025 by UZE taxi customers based on the Location Based Services ensured by GNSS. A total number of 50 taxis were actively collecting GDPR conform and anonymous LCMM data, evaluation is targeting the WLTP data sets for LDT Mobility use case design.

Table 6: Example of Habibi Taxis collecting LCMM Data

Vehicle	Σ Trip Count	Σ Distance (km)	Σ Duration	Ø Speed (km/h)	Ø Fuel Consumption (l/100km)	Ø CO2 Emission (gCO2/km)
5 Vehicles	435	12,304.5	626:43:54	19.2	8,2	217,3
Hamburg-1	15	393.7	27:43:49	14.9	7,1	188,15
Hamburg-2	8	145.5	10:27:11	13.1	7,8	206,7
Hamburg-3	16	247.9	11:28:53	22.1	5,5	145,75
Hamburg-4	93	3,107.3	156:07:25	18.1	10,6	280,9
Hamburg-5	303	8,410.2	420:56:36	19.7	7,7	204,05

Table 7: Example of Habibi Taxis collecting WLTP Data and (%)-ACC

Vehicle	Ø WLTP low (%)	Ø WLTP medium (%)	Ø WLTP high (%)	Ø WLTP extra high (%)	Ø ACC Cycle (%)	Σ CO2 Emission (kg)
5 Vehicles	61	33	6	1	142.3	2,199.7
Hamburg-1	63	29	6	2	122.2	71.6
Hamburg-2	64	28	7	0	125	27.5
Hamburg-3	57	37	5	1	99.6	36.9
Hamburg-4	62	30	7	1	144.5	545.8
Hamburg-5	60	33	6	0	145.3	1,517.9

The first round of 3DxVerse data collection took place with UZE taxis from May to August in 2025 and showed how to make use of ISO-23795 LCMM data sets with regards to climate protection and decarbonisation of road transport. Tables 6 and 7 give already an indication about the different driving behaviour, in especially with regards to professional drivers, often under severe time pressure. Fuel consumption and linear linked carbon emissions show a variation of average 50% less for the best driver placed in the middle of table 6, a value which was often stated by eco-drive researchers. Compared to this, acceleration measured in %-WLTP acceleration deviation of the driver with highest fuel consumption is directly linked times 26.5 to the carbon emissions in gCO2/km. Both values also aim at giving advice to consumers about the energy efficiency by labelling the difference, as suggested in D8.1 for labelling energy efficiency linked to housing. The LCMM energy efficiency labelling suggested in 3DxVerse can be found for Hamburg in Figure 9.

Trip (f0f3fc13-b57a-4cdb-9a5c-6338ed1fe6d1) 14.06.2025, 22:56:35 -> 15.06.2025, 01:59:50

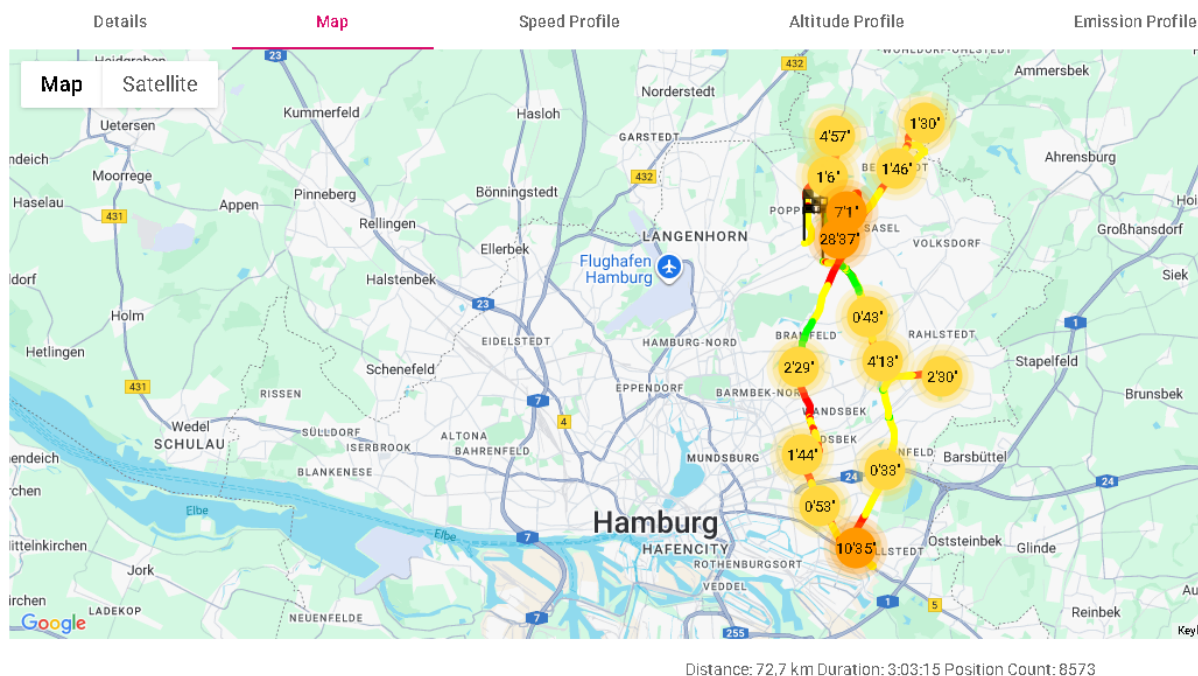


Figure 9: One ISO conform LCMM trip from Taxis in Hamburg

Figure 10 depicts LCMM from Android and iOS APPs installed within the Timisoara Pilot activities in Romania. Here three test vehicles collecting LCMM data from the road network in Romania are shown with regards to mileage, average speed, fuel consumption and carbon emissions. As the main contribution came from vehicle Romania-1, an UBER taxi, most of the data is linked to this vehicle and a comparison of fleet behaviour is not reasonable. Nevertheless, the methodology proved its interoperability by transferring the app functions from Hamburg to Romania, independent of complex mobile networks operated differently, but roaming compatible in both countries.

Independent of roaming, Mobile Networks operate with several background standards in place, enabling customers to change countries, but using their phones worldwide. In the case of LCMM, this is combined with the data evaluation of signals from the global satellite positioning systems (GNSS) which are ensure localisation, timing and the detection of speed profiles. Often, there are configurations modules left to use the same app and software in different regions and countries of the world, in the case of the 3DxVerse pilots, the fully interoperable MNO and GNSS infrastructure guarantees worldwide interoperability. This is illustrated in Table 8 and 9, as well as in Figure 10.

Table 8: Continental LCMM data collected in Timisoara (Romania)

Vehicle	Σ Trip Count	Σ Distance (km)	Σ Duration	Ø Speed (km/h)	Ø Fuel Consumption (l/100km)	Ø CO2 Emission (gCO2/km)
3 Vehicles	150	11,557.8	655:07:13	19.2	8.6	183
Romania-1	141	10,834.2	608:20:31	19.3	8.6	183.5
Romania-2	2	33.4	09:41:02	3.7	12.9	322.7
Romania-3	7	690.3	37:05:40	20	7.1	169.3

Table 9: Continental ACC WLTP data collected in Timisoara (Romania)

Vehicle	Ø WLTP low (%)	Ø WLTP medium (%)	Ø WLTP high (%)	Ø WLTP extra high (%)	Ø ACC Cycle (%)	Σ CO2 Emission (kg)
3 Vehicles	66	19	9	6	118.8	2,115.5
Romania-1	66	19	9	6	118.1	1,987.9
Romania-2	81	17	1	0	89.6	10.8
Romania-3	67	25	7	1	140.6	116.9

Trip (4e4c77a7-76a5-45c7-a1f9-29c5ddaf3a6b) 10.11.2025, 07:24:39 -> 14:51:43

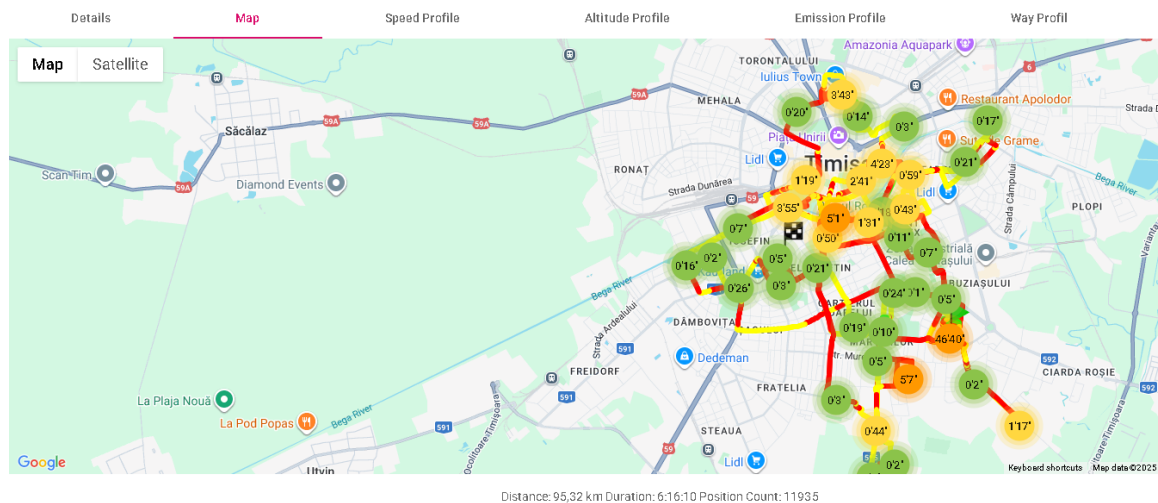


Figure 10: ISO conform LCMM trip from Continental fleets in Timisoara (Romania)

The Aruba pilot shows exactly this type of GSM/GNSS interoperability required as fundamental for project implementation according to the 3DxVerse Grant Agreement. The pilot has a total number of 14 food delivery Light Duty Trucks operating in Dutch Overseas ARUBA.

Table 10: LCMM data collected in Aruba (Dutch Antilles)

Vehicle	Σ Trip Count	Σ Distance (km)	Σ Duration	Ø Speed (km/h)	Ø Fuel Consumption (l/100km)	Ø CO2 Emission (gCO2/km)
14 Vehicles	186	4,606.7	1,912:38:25	5.9	19,7	522
Aruba-1	22	596.9	200:44:23	3.8	24,2	641
Aruba-2	6	307.9	44:43:40	10.2	12,5	331
Aruba-3	3	125.4	25:14:57	9.7	29,4	779
Aruba-4	6	363.6	281:20:54	1.5	19,8	525
Aruba-5	9	62.4	136:18:16	0.7	38,7	1026
Aruba-6	22	261.2	186:22:03	5.5	21,2	562
Aruba-7	9	20.5	45:12:49	1	10,9	289
Aruba-8	8	202.2	227:35:19	3.4	27,7	734
Aruba-9	41	730.2	125:27:34	9.5	11,9	315
Aruba-10	20	896.8	254:58:47	6.4	13,5	358
Aruba-11	7	328	67:16:12	7.4	11,9	315
Aruba-12	7	109.5	73:38:33	1.2	32,5	861
Aruba-13	22	489.1	198:09:17	7.8	23,3	617
Aruba-14	4	113	45:35:41	2.6	36,4	965

Table 11: Aruba LCMM data analysing %-ACC WLTP

Σ CO2 Emission (kg)	Σ Trip Count	Ø WLTP low (%)	Ø WLTP medium (%)	Ø WLTP high (%)	Ø WLTP extra high (%)	Ø ACC Cycle (%)
14 Vehicles	186	69	22	4	0	79,7
Aruba-1	22	74	18	2	0	81,1
Aruba-2	6	54	32	13	0	110,4
Aruba-3	3	63	29	7	0	83,8
Aruba-4	6	66	29	4	0	71,6
Aruba-5	9	65	0	0	0	13,0
Aruba-6	22	77	19	2	0	81,8
Aruba-7	9	77	8	1	0	67,8
Aruba-8	8	62	12	1	0	57,0
Aruba-9	41	63	30	7	0	97,2
Aruba-10	20	70	25	4	0	80,6
Aruba-11	7	71	24	5	0	91,8
Aruba-12	7	84	12	0	0	73,6
Aruba-13	22	66	28	5	0	78,0
Aruba-14	4	53	13	6	0	60,1

Trip (92878716-e1e0-40a6-99ce-c9d162a1b3f6) 10.11.2025, 15:07:30 -> 18:04:11

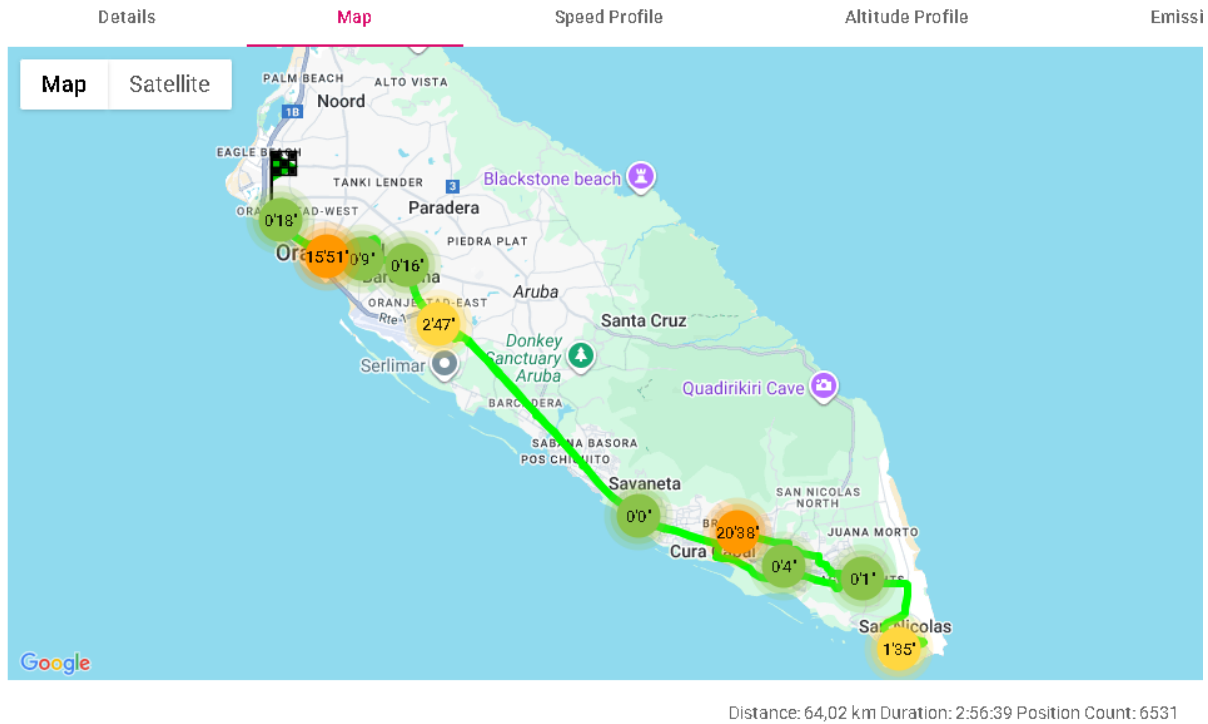


Figure 11: ISO conform LCMM trip from Caribbean Dutch ARABU

To summarize: User inclusion took place with 50 drivers from taxi fleets in Hamburg (Germany), employees of 3DxVerse partner Continental in Timisoara (Romania) and a logistics fleet operator for food delivery with 14 light-duty-trucks in Aruba (Dutch Caribbean). All of them collected LCMM data needed to calibrate the digital twin for the planned mobility use case.

3. SUSTAINABLE AIRPORT AND LIVING ENVIRONMENT USE-CASE (ARUBA PILOT)

3.1. Scope, Context & Use-Case Overview

The Aruba pilot develops an operational Digital Twin of Queen Beatrix International Airport (AUA) to enable real-time monitoring of airside and landside operations for sustainability and community transparency. Defined as “a virtual replica of a physical system continuously updated with real-time data” (How Digital Twin Technology Is Helping Heathrow Cut 30,000 Tonnes of CO₂ Emissions | Smart Spatial Blog, n.d.), this Digital Twin integrates flight data, environmental sensors, and operational systems to model airport activities and their impacts—such as fuel burn, noise, and pollutant emissions (CO₂, NO_x, SO_x, PM). Airports worldwide already use such technology to optimise routing and energy use, reducing fuel consumption and CO₂ emissions (How Digital Twin Technology Is Helping Heathrow Cut 30,000 Tonnes of CO₂ Emissions | Smart Spatial Blog, n.d.).

FHC Corp N.V., as Aruba’s pilot lead, is developing this twin to feed data into the AHOP (Aruba Happy One Pass) platform and align with the airport’s carbon-accreditation pathway (3DXVERSE - FHC Interview, n.d.; Pinto, 2025). The Aruba Airport Authority (AAA) has committed to becoming “one of the most sustainable airports in the Caribbean” by 2030 (Pinto, 2025; Carbon Emissions Policy, n.d.). This pilot supports that ambition by enabling data-driven insights and decision support, allowing stakeholders to explore new ground and terminal procedures or infrastructure changes in a simulation environment before physical implementation.

The pilot expands the Digital Twin to cover four critical operational domains:

- **Airside Operations:** The pilot maps actual flight trajectories using ADS-B data and links them to modelled emissions (CO₂, NO_x, SO_x, PM) and noise footprints. The focus is on accurately characterising real operations rather than altering flight paths. By comparing different aircraft types, existing runway-use patterns, or time-of-day operations, the system provides insights into which flights contribute most to emissions or noise impacts.
- **Ground Operations:** The twin monitors aircraft movements, Auxiliary Power Unit (APU) usage, and service-vehicle activity. Monitoring APU run-time is crucial, as excessive usage “contributes to noise and emissions of CO₂ and ultrafine particles” affecting workers and nearby communities (Clark & Clark, 2025). Similar to Copenhagen’s AI system (Clark & Clark, 2025), the Aruba pilot will flag excessive APU/GPU use and evaluate strategies such as single-engine taxiing (SET) and optimal gate procedures to reduce fuel burn during turnarounds.
- **Terminal and Landside Flows:** The twin models energy use, passenger movement, queue lengths, and staff logistics. Studies such as Brussels Airport’s digital-twin work show that environmental modelling enables accurate baseline CO₂ estimation and virtual testing of energy-saving measures (Barbano et al., 2024). In Aruba, the system will simulate peak-hour crowding and dynamic HVAC/lighting adjustments to optimise terminal energy consumption.
- **Traveller Carbon Footprint & Engagement:** Finally, the twin integrates airside, ground, and terminal data to calculate a daily CO₂ footprint per passenger. This data links to the passenger’s digital identity within the AHOP wallet, already utilised for the biometric “Happy One Pass” system (Pinto, 2025). The pilot introduces gamified offset pathways, allowing travellers to earn credits or rewards for supporting certified sustainability projects. Gamification has proven effective in motivating eco-friendly behaviour (Gamification in Tourism: Encouraging Sustainable Travel Practices, n.d.; Katlene O. Cacho-Laurejas, 2025), with examples including NFT-based reward schemes for carbon-neutral hotels (Katlene O. Cacho-Laurejas, 2025). This mechanism turns carbon tracking into an educational experience, engaging both residents and visitors in climate action.

Overall, this integrated Digital Twin serves as an evidence base to understand and progressively optimise airport operations. By modelling the impacts of operational and infrastructure measures before implementation, it supports data-driven mitigation—aligned with ACI/ICAO carbon-accreditation frameworks (Barbano et al., 2024; Pinto, 2025)—and feeds validated metrics into Aruba’s national climate goals.

3.2. Stakeholders & Partner Involvement

The pilot consortium connects local government and residents with technological partners. Key stakeholders include the Aruba Airport Authority (AAA, operator of AUA) and the Ministry of Infrastructure/Transport, local tourism and environmental agencies, the airlines serving Aruba, and the surrounding communities (highly sensitive to aircraft noise and air quality) (ICAO Committee on Aviation Environmental Protection (CAEP, 2025).

These groups work closely with the project partners (such as ADECS, FHC, iLabs/ILABS, T-Systems, ESRI, THUAS, etc.) to provide data, define use-cases, and validate results. Each of these parties fulfils a specific role (RACI model) within the LDT development, as detailed in the table below.

Table 12: Aruba stakeholders table

Stakeholder	RACI Role	Responsibilities
Aruba Airport Authority (AAA)	Accountable	Responsible for overall pilot success at AUA; defines data access and operational requirements; ensures safety and regulatory compliance; provides airport-logistics data (baggage, gate data, etc.). See UC4/UC5 for data integration.
Ministry of Infrastructure/Transport	Accountable / Consulted	Oversees national aviation and environmental regulations; manages permits for ADS-B usage and noise-standards; consulted for KPI and policy alignment.
ADECS, FHC (local IT partners)	Responsible	Technical implementation of the LDT; collect/enrich flight data (ADS-B, AODB); build 3D tools for flights, obstacles, noise zones, CO ₂ models; implement airport-specific modules and simulations.
ILABS	Responsible	Leads trust & security framework (DevSecOps); ensures privacy-by-design; ISO 23795-1 data quality; manages authentication (iSHARE); ensures GDPR compliance.
ESRI	Responsible	Provides 3D geospatial backbone (ArcGIS); builds data layers and 3D scenes following EU LDT standards; supports public dashboards and open-data integration.
THUAS (The Hague University)	Responsible / Consulted	Leads participatory processes; organises co-creation workshops; analyses usability and citizen feedback; bridges technology and end-users (pilot writing).
Airlines & Airport Operations Teams	Consulted	Provide flight-planning and operational data; validate feasibility of proposed improvements (e.g., shorter waiting times).

Local Community (residents, businesses)	Consulted / Informed	Engaged through forums/workshops (validating noise maps, visualisations); provide informal insights on noise & climate; receive information via public dashboards (noise maps, CO ₂ wallet).
Tourism & Environmental Agencies	Consulted	Align LDT with sustainability goals; use data for environmental statistics (noise norms, emissions reductions); promote sustainable aviation.
Public / Travellers	Informed	Access personalised travel-impact data via the digital CO ₂ wallet and public interfaces; strengthened awareness and accountability.

This multi-actor structure follows the 3DxVERSE principle of integrated governance: each partner contributes to the data, technical, governance, or participation layer. For example, ERTICO serves as the consortium coordinator, ensuring alignment and knowledge exchange across all pilot sites (including Aruba). ILABS manages security and privacy aspects, while THUAS leads stakeholder engagement. Local authorities (AAA, MOT) hold final responsibility for regulatory compliance, whereas technology partners (ADECS, FHC, Ambrosys, T-Systems, ESRI) are responsible for development and implementation. Governments, citizens, and environmental organisations are consulted and informed through transparent reporting, ensuring decision-making is supported by all stakeholders (ICAO Committee on Aviation Environmental Protection (CAEP), 2025).

3.3. Data Architecture and Sources

The Aruba sustainability pilot requires integrating several data streams into a unified platform.

Flight Operations: Flight operations data from the Airport Operational Database (AODB) provides key flight milestones such as landing, gate events, pushback, and takeoff; an AODB centralises airport schedules and statuses (Indra, n.d.). When aligned with external ADS-B trajectory data (e.g., ADECS Radarcape), this produces a precise timeline of each aircraft on the ground and in the air, enabling analysis of delays and inefficiencies.

Noise Monitoring: Noise-monitoring data comes from fixed monitors that record metrics such as LAeq, SEL, and Lmax. These real measurements compare and validate model-based noise predictions. Tools like AEDT generate contours following ECAC Doc 29/ICAO standards, while airports such as Paris–CDG correlate monitored noise events with radar tracks (ICAO Committee on Aviation Environmental Protection (CAEP), 2025). Combining model output with measurements ensures accurate noise-exposure assessments, while recognising that weather and other environmental factors influence measured values and are not included in the calculations.

Surface Access: Surface-access data is gathered from GPS-based vehicle probes (buses, taxis, apps) and fixed sensors such as LIDAR or cameras that count vehicles by type. These datasets show the timing and volume of ground-transport trips. Although no specific source was found for ISO 23795-1 or airport LIDAR use, such sensor-based mobility data is standard in transport research. This allows attribution of on-road emissions and access impacts to the airport.

Energy and Utilities: Energy and utilities data comes from smart meters/BMS sub-meters for terminal electricity use—airports typically consume around 180 million kWh/year (Energy Management for Airports, 2025). EV chargers, water-meter logs, and waste-service invoices add further detail. This information feeds into an Energy Management System, similar to EMS “Data Layer” architectures aggregating smart-meter and sensor inputs (Nark & BuildingIQ, 2016). These data allow the twin to link operational changes to energy outcomes.

Emissions and Ground Equipment: Emissions and ground-equipment data include APU/GPU run times, GSE engine hours, and fuel logs. Ramp equipment typically uses telemetry (Ground Ops of the Future, n.d.). These enable estimation of Scope 1 (airport-owned) and Scope 3 (aircraft/APU/GSE) emissions. APUs are a major ground-emission source (News: New APU Emissions Control Technology Reduces Ground Emissions and Costs, n.d.); airports such as Barcelona save ~58,000 t CO₂ annually through mandatory GPU use (“EFFICIENCY ON THE GROUND,” n.d.), while Heathrow achieves similar reductions (~100,000 t/yr) through ground-efficiency measures. These figures are indicative for other airports and provide context for potential benefits.

Traveller Engagement: Traveler-engagement data is collected via the AHOP digital wallet, which logs itineraries, CO₂ footprints, ground-transport choices, offsets, and sustainable purchases, as well as interactions with eco-education hubs. Passenger surveys show strong willingness to act: 9 in 10 travellers would pay more or change habits to reduce emissions, and ~76% would share carbon/travel data to optimise their routes (Aerospace Global News, 2025). Linking wallet data with operational datasets reveals how passenger behaviour influences airport-wide emissions.

Table 13: Data Inventory and Sources for Aruba Pilot

Category	Data	Source / Sensor
Flight Operations	Milestones (landing, gate, pushback, take-off)	AODB
	Aircraft trajectory & position	ADS-B (ADECS Radarcape)
Noise	LAeq, SEL, Lmax	Noise monitors
	Noise contours (model output)	AEDT / ECAC Doc 29
Surface Access	Vehicle GPS trips	GPS probes (taxis, buses, apps)
	Vehicle counts	LIDAR / cameras
Energy & Utilities	Electricity, HVAC, water, waste	Smart meters / BMS
	EV charging data	EV chargers
Emissions & Ground Ops	APU/GPU usage	APU/GPU logs / telematics
	GSE engine hours & fuel use	GSE telematics / fuel logs
Traveller Engagement	Itinerary & CO ₂ footprint	AHOP wallet
	Mode choices, offsets, sustainable actions	AHOP wallet

Combined, these data sources create a unified database connecting flight timelines, noise events, ground-access patterns, and energy/emissions profiles. This integrated fusion allows the pilot to evaluate both direct environmental indicators (emissions, noise) and the behavioural factors that shape them.

3.4. Analytical Models & Simulations

The pilot uses the integrated data streams to run a suite of interconnected models that convert operational data into insights and, where feasible, explore the potential impacts of selected ground and terminal measures.

3.4.1. General Description

The simulation framework comprises three primary analytical components:

Ground Emissions Model: This model estimates CO₂ and pollutant outputs (NO_x, SO₂, PM) from taxiing, engine type, APU/GPU usage, and Ground Support Equipment (GSE) operations. Activity data is converted to fuel burn using ICAO/EPA emission factors. Based on observed operations and literature values, the model assesses the potential impact of measures such as single-engine taxiing (SET)—which Eurocontrol’s Sustainable Taxiing Taskforce highlights as a pathway to significant fuel and CO₂ reductions (2024)—and evaluates increased GPU/FEGP adoption, a strategy that has produced substantial CO₂ savings at airports with mandatory GPU policies (“Efficiency on the Ground,” n.d.).

Noise Impact Model: This model generates noise contours based on ECAC Doc 29/ICAO 9911 standards using ADS-B paths and aircraft characteristics. Outputs such as LAeq and Lmax are compared with measured data from noise monitors to validate model behaviour, while acknowledging that weather and other environmental factors influence measured values. The model supports flight-to-flight and aircraft-type comparisons, helping identify which real operations contribute more or less to community noise exposure.

AI-Enabled Pattern Analysis: These tools (e.g., clustering, anomaly detection, regression models) identify deviations and operational patterns across flight, emission, noise, and passenger datasets. Algorithms flag unusual events—such as extended taxi times or excessive APU usage—and cluster similar operations to highlight systemic bottlenecks or community “hotspots.” Machine-learning-supported analytics have shown potential to improve airport efficiency and environmental performance (Mba, 2024).

3.4.2. Conclusion

Together, these components form an Integrated Digital Twin that supports the assessment of operational or policy measures before or during implementation, specifically targeting ground and terminal processes rather than alternative flight routes. Managers can evaluate interventions—such as expanding GPU deployment or improving taxi and gate procedures—and visualise the projected effects on fuel use, emissions, and noise. Integrated smart-management approaches are associated with measurable reductions in airport greenhouse-gas emissions (Mba, 2024). Overall, the twin turns raw data into actionable foresight for a more sustainable airport.

3.5. Platform Architecture & Components

The Aruba pilot includes several interconnected interface and backend components.

3.5.1. General description

The platform architecture consists of four primary modules:

Operational Dashboard (Restricted Access): This component gives airport operations managers a secure, real-time view of ground activity by integrating ADS-B flight data, taxi movements, and APU/GPU usage into interactive maps and 3D visualizations. It flags anomalies—such as long taxi times

or excess APU usage—and allows operators to explore the operational impact of different gate assignments or optimised push-back procedures. This approach follows the 3DxVERSE principle of providing insight- and scenario-supported dashboards for ground operations.

Public Digital Twin Hub: This hub provides open, non-sensitive information to the community, including real-time CO₂ counters, interactive noise-contour maps, and 3D flight-path replays. By combining ADS-B trajectories with noise-model outputs, the hub visualises how air traffic creates noise “hotspots” around the airport. It supports multilingual access (EN/NL/Papiamento) and user feedback, aligning with the pilot objective to inform travellers and use transparent noise/flight-path visualization to deepen engagement.

AHOP CO₂ Wallet: Integrated into the Aruba Happy One Pass (AHOP) loyalty system, this wallet calculates each traveler’s individual carbon footprint based on flights and ground transport. It offers certified offset options and logs purchased offsets. Future phases will introduce gamification elements, such as badges and rewards, to promote sustainable travel. This fulfills the use-case requirement to “inform travellers via a CO₂ wallet” through personalized environmental feedback.

Data Fabric: This cloud-based backend ingests ADS-B, operational logs, and sensor feeds (noise, energy) via secure APIs and IoT gateways into an NGSI-LD-compliant context broker. Data are tagged with provenance and anonymized when needed. A microservices architecture applies standard models aligned with ISO 23247 and ISO 23795-1, while a streaming layer (e.g., Kafka) supports low-latency updates. This implements the necessary technical groundwork for data collection and simulation (APIs, sensor/IoT gateways, consent- and provenance-aware pipelines) and ensures GDPR-compliant EU hosting.

3.5.2. Conclusion

Together, these modular cloud components—maps, dashboards, analytics, and citizen tools—form an interoperable Local Digital Twin platform “built from modular components” that is expandable with new data sources and models. By continuously ingesting data and producing standardized metrics and visuals aligned with D6.2 KPIs, the system ensures that airport operations, community engagement, and traveler-facing tools all rely on the same trusted open-data foundation.

3.6. Pilot Evaluation (KPIs)

The pilot evaluates its impact using four distinct KPI categories, designed to quantify improvements in efficiency, sustainability, and stakeholder engagement.

Operational KPIs: These measure airport-efficiency improvements, including average taxi-out time, Auxiliary Power Unit (APU) runtime per turnaround, the share of turnarounds using Ground Power Units (GPU) instead of APUs, and total turnaround duration. Outlier detection flags abnormal events—such as taxi times significantly above historical norms—supporting rapid intervention. These indicators align with core 3DxVERSE metrics such as “APU minutes” and “taxi time,” enabling the quantification of gains in airport-authority processes.

Environmental KPIs: These assess sustainability outcomes, including monthly CO₂ per turnaround (derived from engines and ground power), weekly noise-exceedance events, and pollutant concentrations (NO_x, SO_x, PM) where available. Spatial analytics identify persistent noise or emission hotspots around the airport. Trends such as declining gCO₂e per flight-km or reduced APU fuel burn align with mobility-decarbonization KPIs, indicating whether operational or infrastructure measures are effective, with the Digital Twin providing the analytical evidence base rather than direct control.

Engagement KPIs: These track participation by travellers and citizens. Metrics include monthly active users of the AHOP CO₂ wallet, the volume of offset transactions, and usage statistics of the public hub (page views, map interactions, feedback). Surveys measure satisfaction and behavioral change, such as whether personalised CO₂ data influenced travel decisions. These indicators parallel catalogued KPIs like “passenger engagement (CO₂ data/offset),” demonstrating whether digital tools effectively raise awareness and encourage greener behaviour.

Institutional KPIs: These evaluate how organisations adopt and utilize the Digital Twin’s outputs. They include counts of sustainability-report sections or regulatory filings that incorporate LDT data (e.g., CO₂ summaries or noise maps) and references to the twin in policy planning or investment cases. Demonstrating that the Aruba Airport Authority (AAA) uses LDT analytics in its reports and decisions confirms that the twin is actively shaping governance and embedding insights into institutional processes.

Together with AI-based pattern recognition, these KPIs provide actionable insights rather than raw metrics. As the framework states, the evaluation will “quantify environmental, operational, and social benefits” and deliver an adaptive, data-driven feedback loop. Deviations—such as falling short of a CO₂-reduction target—can trigger targeted operational reviews or further analysis, prioritising follow-up actions and supporting continuous improvement in airport operations, community transparency, and sustainable planning.

3.7. Aruba Use Cases

The Aruba pilot focuses on four integrated use cases (UCs), each designed to deliver operational improvements, environmental transparency, and traveler engagement. Each UC is framed with specific goals, defined scope, and measurable outcomes.

3.7.1. UC4 — Flights Monitoring & Registration

The goal of this use case is to fully automate the tracking of every flight milestone (landing, taxi, gate-in/out, pushback, take-off) by fusing ADS-B data with the airport’s operational databases. Instead of manual logging, ADS-B messages from each aircraft are processed to derive precise flight trajectories and timing. Research shows that ADS-B streams enable data-driven analysis of aircraft movements and operational milestones (Schultz et al., 2021). Capturing these events in real time feeds directly into emissions and noise models, since knowing exactly when an aircraft spends time in each phase (taxi, climb, cruise, etc.) supports more reliable environmental assessments. All flight tracks are visualised in a live 3D/4D digital twin of the airport, allowing operators to observe the entire site and analyse actual operations over time. Enriching each flight with metadata (aircraft type, weather at the time, active runway) further improves the reliability of downstream analyse

Scope & Functions:

- Automated Capture: Detection of key milestones (e.g., lift-off, touch-down, pushback) via ADS-B combined with Airport Operational Database (AODB) inputs without human intervention (Schultz et al., 2021).
- 3D/4D Visualization: Real-time visualization of live and historical flight paths in the airport model (digital twin) (Sulmona, 2025).
- Data Enrichment: Contextualization of each operation with aircraft model, weather conditions, and runway surface status.
- Data Feeds: Provision of exportable feeds for analytics, reporting, and compliance.

KPIs:

- Accuracy of automated milestone detection (versus manual ground-truth logs).
- Data latency (time from actual event to recorded entry).

- Adoption rate (e.g. number of operational sessions using the automated data).

3.7.2. UC5 — Flights & Limitations (Obstacle Limitation Surfaces)

This use case maps the airport’s regulatory 3D “envelope” and compares it to actual and published flight paths, improving safety and planning. ICAO Annex 14 defines Obstacle Limitation Surfaces (OLS)—invisible 3D zones around runways beyond which no structures may protrude (ICAO Annex 14 (Aviation OIS)—ArcMap | Documentation, n.d.). The system renders these OLS geometries in 3D, clarifying where cranes, towers, or wind turbines would infringe on protected airspace. It also generates “tolerance corridors” around standard flight routes to highlight how much lateral or vertical deviation is safe. A “what-if” planner lets users add a virtual structure (e.g., a proposed high-rise or turbine) and immediately see if it penetrates any OLS according to Annex 14 criteria (Aviation Consulting & Engineering Solutions for Airports, 2024). Public-friendly overlays simplify this information for the community, showing color-coded height limits on a map to explain building restrictions. By raising awareness of these rules, stakeholders can make better-informed decisions on land use and development (ICAO Annex 14 (Aviation OIS)—ArcMap | Documentation, n.d.) (Aviation Consulting & Engineering Solutions for Airports, 2024).

Scope & Functions:

- **3D Modeling:** Modeling of ICAO Annex 14 obstacle limitation surfaces (approach, take-off, transition zones) around AUA (ICAO Annex 14 (Aviation OIS)—ArcMap | Documentation, n.d.).
- **Tolerance Corridors:** Visualization of flight route “tolerance corridors” along standard procedures, showing allowable deviation from the centerline.
- **Interactive Planning Tool:** A feature allowing planners to insert hypothetical obstacles (e.g., construction cranes) to instantly test compliance with safety surfaces (Aviation Consulting & Engineering Solutions for Airports, 2024).
- **Public Maps:** Public-oriented map overlays explaining maximum permitted structure heights and flight path clearances.

KPIs:

- Number of OLS compliance checks or violation assessments performed.
- Number of planning queries resolved using the tool.
- Average resolution time for construction permits (approval/rejection decisions).

3.7.3. UC6 — Flights & Environmental Impact (Noise)

This use case provides robust noise-exposure analysis for communities around the airport. The system calculates aircraft noise contours around AUA using established methodologies (e.g., ECAC Doc.29/AEDT) and compares modelled outputs with data from fixed noise monitors. For each flight, its 4D ADS-B trajectory is linked to a corresponding noise footprint on the ground, enabling flight-by-flight analysis. By comparing modelled contours with actual measurements, the airport can verify model behaviour while recognizing that weather and other environmental factors influence noise readings.

The system focuses on comparing actual operations — for example, evaluating differences between aircraft types (e.g., B737 vs A320), time-of-day patterns, or runway-use variations within existing procedures. These comparisons help identify which real-world operations contribute to community noise exposure, strengthening transparency and stakeholder communication.

• Scope & Functions:

- Compute noise contours around the airport using ECAC Doc.29/AEDT methodologies for current and historical traffic.

- Validate modeled noise against continuous data from fixed monitors (ensuring model fidelity (*ICAO Annex 14 (Aviation OIS)—ArcMap | Documentation*, n.d).
- Associate each flight trajectory with its noise footprint to analyze contributions of individual flights.
- Produce community-facing outputs (contour maps, time-of-day noise profiles, etc.) to explain exposure levels.
- **KPIs:**
 - Number of noise assessment reports delivered to stakeholders.
 - Correlation between modelled noise metrics and monitor data.
 - Number of flight- or aircraft-type comparison analyses performed (noise exposure).
 - Number of community-facing noise outputs published (e.g. maps, time-of-day profiles)

3.7.4. UC7 — CO₂ Wallet (AHOP Integration)

This use case creates a personalized carbon-accounting feature for travelers. For each passenger, the system calculates the CO₂ emissions of their journey using detailed flight data (aircraft type, route, fuel burn estimates, etc.) (*ICAO Annex 14 (Aviation OIS)—ArcMap | Documentation*, n.d). When data and budget allow, it can also include “first/last mile” surface trips. The computed CO₂ value is stored in the traveler’s Aruba Happy One Pass (AHOP) digital wallet. The wallet interface then offers certified offset options and incentives; for example, users could earn “green miles” or points for choosing lower-carbon flights or purchasing offsets. Over time, travelers see a cumulative history of their footprints and offset actions, enabling them to track and reduce their environmental impact.

Scope & Functions:

- **Emission Calculation:** Calculation of per-passenger CO₂ emissions for each flight using actual flight conditions and aircraft performance data (*ICAO Annex 14 (Aviation OIS)—ArcMap | Documentation*, n.d).
- **Extended Mobility:** Extension of calculations to ground transportation (taxi, ride-share) when possible. Store each journey’s CO₂ in the traveler’s AHOP digital ledger.
- **Digital Ledger:** Storage of each journey’s CO₂ data in the traveler’s AHOP digital ledger.
- **User Dashboard:** Provision of a dashboard displaying historical emissions and offsets for user awareness.

KPIs:

- Percentage of passengers who receive (opt-in to) personalized CO₂ figures.
- Number of wallet users purchasing offsets.
- Engagement metrics: wallet usage rate, offset transaction volume, reward redemptions.

3.8. Data Governance, Ethics & Privacy for Aruba Pilot

The Aruba digital twin must adhere to GDPR and local privacy laws to build trust. Data minimization is enforced – only the minimum traveler data needed is collected and stored (*IAPP*, n.d.). For instance, CO₂ figures can be recorded under an anonymized wallet ID without retaining full personal identifiers. The processing has a clear legal basis: explicit consent is requested for CO₂ wallet and personalization features, while aggregated environmental data (noise contours, emission statistics) is processed under legitimate interest or public task. Technical and organizational security measures are implemented by design: personal data is encrypted both at rest and in transit (encryption is explicitly recommended by *GDPR Art.32*) (*Encryption - General Data Protection Regulation (GDPR)*, 2025). Access to sensitive data is protected by role-based permissions and audit logging. The project maintains full transparency — model assumptions and code changelogs are documented publicly, and FAQs/community briefings

explain data usage. Ethically, no hidden profiling or automated decision-making beyond user consent occurs; any operational decisions (e.g. alerts) include human oversight to prevent unfair outcomes.

- **Minimization:** Store only essential data (e.g. pseudonymized traveler IDs for linking offsets) (*IAPP*, n.d).
- **Legal Basis:** Use explicit opt-in consent for personal CO₂ features; rely on legitimate interest or public mandate for anonymized community data.
- **Security:** Apply strong encryption (as per GDPR Art.32 recommendations) (*GDPR*, 2025) and RBAC controls; maintain audit trails for data access.
- **Transparency:** Publish data processing principles, algorithm documentation, and open change logs; engage the public through FAQs and briefings.
- **Ethical Safeguards:** Prohibit non-consensual profiling; ensure humans review any automated alerts or analytics affecting operations.
- **KPIs:**
 - Completion of required Data Protection Impact Assessments (DPIAs).
 - Zero personal data breaches or security incidents.
 - Positive stakeholder trust metrics (community surveys, user feedback).

3.9. Implementation Plan & Timeline for Aruba Pilot

The Aruba airport digital twin will be deployed in a phased, agile manner, ensuring foundational systems are stable before scaling up. Each phase has specific deliverables, timelines, and validation steps, with ongoing QA and KPI tracking. We draw on best practices from other airport twin projects, such as Schiphol's GIS/BIM twin and Brussels Airport's energy twin, to guide our rollout (Barbano et al., 2024).

3.9.1. Phase 1 – Foundations

Focus: Core infrastructure and data onboarding.

- **Infrastructure Setup:** Configure the cloud and on-site environments, including the NGSI-LD context broker, ArcGIS Enterprise server, and Cesium 3D engine. Install and align the ADECS ADS-B antenna for near real-time flight tracking and secure Airport Operational Database (AODB) API access. Begin ingesting flight and ground-equipment telemetry via NGSI-LD-compliant pipelines (Otsu & Maso, 2024).
- **Data Integration:** Import airport GIS layers and BIM/CAD models via FME or equivalent ETL tools, following Schiphol's approach to creating unified 3D scene layers. Establish a baseline spatial model for the airport. Conduct a Data Protection Impact Assessment (DPIA) following D5.1 guidance and implement an iSHARE-based identity and access framework to ensure GDPR and data-space compliance.
- **Initial Stakeholder Engagement:** Hold kickoff workshops with ACA sustainability teams, airside operations, and community representatives. Collect requirements, present early mock-ups of the twin, and prepare staff training plans. Early co-creation builds alignment and organisational buy-in.

3.9.2. Phase 2 – MVP Development

Focus: Build and validate the minimum viable twin.

- **MVP Construction:** Develop core functionalities of the twin. Stream live data (flights, vehicles, utilities) into the GIS/Cesium visualization. Implement basic analytics: calculate flight CO₂ emissions and noise footprints in real time. Leverage WP3 data models (NGSI-LD) to harmonize these inputs (Otsu & Maso, 2024).

- **Model Validation:** Validate emissions and noise outputs by comparing modelled results with real measurements. This involves checking whether the digital twin produces consistent behaviour when compared with historical fuel-burn data and noise-monitor readings. Variations between modelled and measured values are expected, as the calculations do not include external influences such as weather, humidity, ground reflections, or atmospheric conditions. The goal is to confirm that the model performs within reasonable expectations.
- **User Training & Feedback:** Conduct hands-on training sessions for airport stakeholders (e.g., ACA sustainability team, airside operations) using the dashboard and AHOP integration. Introduce community representatives to the platform (showing live CO₂ maps and noise levels). Collect feedback to refine UI/UX and ensure the MVP meets user needs (leveraging WP6 dashboard toolkits). This iterative loop follows best practice of co-creation in digital twin pilots.

3.9.3. Phase 3 – Expansion

Focus: Scale up and optimize the twin.

- **Full-Scale Deployment:** Extend the twin to cover all airport processes. Integrate additional data sources (e.g., ground-vehicle movement, building-energy meters). Enhance platform capabilities—such as XR/AR interfaces for passenger CO₂ credentials and carbon-offsetting options via the AHOP app. Enable limited scenario exploration where feasible: for example, operators may compare different flight types or operational patterns to observe variations in emissions or noise. The twin can provide high-level insights to support longer-term sustainability discussions (e.g., energy upgrades or infrastructure improvements), but not detailed flight-route scenario modelling.
- **CO₂ Wallet Scaling:** Deploy the full production version of the AHOP CO₂ Wallet. Transition from the alpha (MVP) to a fully integrated feature within the AHOP platform. Introduce certified carbon-offset options and reward mechanisms (e.g., Green Miles, badges, redemption tiers) to incentivise sustainable travel behaviour. Track adoption rates, offset purchases, and behavioural changes across passenger segments. This directly fulfils the Aruba use-case objective to “inform travellers via a CO₂ wallet.”
- **OLS Rollout:** Deploy the full Obstacle Limitation Surfaces (OLS) toolkit, enabling planners to run compliance checks for cranes, towers, or proposed developments. Provide simplified, public-facing OLS maps showing maximum allowable structure heights.
- **Community Engagement:** Hold public workshops and an open “Digital Twin Day” to present live dashboards to local citizens and tourism stakeholders. Demonstrate how the twin supports Aruba’s carbon goals. Use these events to gather broader feedback and raise awareness.
- **Training and Handover:** Provide comprehensive training to airport staff on system operations and maintenance. Finalize documentation. Ensure at least ~20 airport users and 10 community representatives are proficient with the tools.

3.9.4. Cross-Cutting Activities & KPIs

Focus: Quality, monitoring, and success metrics apply throughout.

- **Quality Assurance:** Implement continuous QA practices. This includes automated testing of data flows and model outputs, code reviews, and data validation routines. For example, any ADS-B data dropout triggers an alert and fallback to alternative data (scheduled flights) with an explicit QA flag. Adopt a DevSecOps pipeline so that each software update passes security scans and regression tests, embedding 3DxVERSE security patterns from WP5.
- **KPI Tracking:** Define clear indicators at project start. These include schedule adherence (e.g., ≥95% tasks on time), model accuracy targets (e.g., emissions predictions within 10% of measured values), and usage metrics (e.g., number of active users, dashboards accessed). Use the WP6 dashboard framework to display these KPIs in the project cockpit. Hold regular review meetings to check milestones against plan.
- **Success Indicators:** The pilot will be deemed successful if (a) all phase deliverables meet their deadlines, (b) the twin’s models are validated to accuracy targets (as per Brussels case

(Barbano et al., 2024)), and (c) user adoption goals are met (e.g., ≥ 20 staff trained, ≥ 10 community events with positive feedback). Measuring stakeholder satisfaction (via surveys) and system uptime ($\geq 99\%$) are also key. This phased, metrics-driven rollout ensures the twin's operational readiness and public value are demonstrable.

4. CONCLUSION

Deliverable D8.4 establishes the implementation plan for the 3DxVERSE pilots in Hamburg, Aruba and Timișoara. The document sets out the structured roadmap, data foundations and methodological approach that will guide the construction of the Local Digital Twins in the coming phases. It translates the conceptual and technical work from WP6 and WP7 into a clear operational pathway for WP8, defining how each pilot will be built, tested and progressively expanded.

The deliverable outlines how each pilot has identified its relevant data sources, clarified its use-case logic and prepared the initial modelling and evaluation structures that will support the development of the Local Digital Twin environments. This includes organising mobility, airport and environmental datasets, defining early analytical models and mapping the collaboration between partners and authorities. These elements form the practical starting point from which the LDTs will be constructed and refined.

For Aruba, the implementation plan describes how future integration of ADS-B data, airport operational information, noise metrics, emissions modelling and CO₂-related components will be brought together within the local twin. Hamburg and Timișoara follow corresponding frameworks using their mobility datasets, confirming that a shared structure can be applied even though each pilot remains in its construction phase. The document therefore acts as a coordinated blueprint for how data, models and workflows will be assembled into operational Local Digital Twins.

The KPI framework included in D8.4 defines how performance will be evaluated in the pilots. These indicators will guide future assessment of environmental, operational and engagement outcomes and ensure a consistent method for monitoring progress as the LDTs evolve. The deliverable also explains how results from this construction phase will feed forward into later iterations of WP8, supporting refinement, governance alignment and eventual scaling across the pilot sites.

Citizen engagement is a core element of WP8, and D8.4 establishes the groundwork for how communities, travellers and local stakeholders will be involved as the pilots develop. The deliverable highlights user engagement as an explicit objective and links it to the Digital Commons principles from WP4 and the trust and privacy requirements from WP5. Although the pilots are still under construction, the document prepares the structures needed for future interaction, including public-facing mobility insights for mobility pilots, and the anticipated integration of environmental and CO₂ information into Aruba's AHOP environment. These foundations ensure that citizen participation can grow in parallel with the technical development of the Local Digital Twins.

Overall, D8.4 serves as a comprehensive and robust implementation framework. It provides the roadmap, structure and technical foundations required for constructing the Local Digital Twins, ensuring that the next stages of development can proceed in a coordinated, traceable and scalable manner as the pilots move from planning into active deployment.

ANNEXES

Annex A — Full KPI Matrix

Dimension	Indicator	Baseline (T0)	Target	Source/Frequency	Owner
Operations	Avg taxi-out (min)	16.5	-10%	AODB/ADS-B — monthly	AAA Ops
Operations	APU runtime per turn (min)	21.0	-20%	Ground logs — monthly	Handlers
Environment	CO ₂ /turnaround (kg)	280	-10%	Modelled + ops — monthly	AAA Sustainability
Environment	Noise events > threshold (#/wk)	48	-15%	Noise monitors — weekly	ADECS/AAA
Engagement	Wallet MAU (travellers)	0	+2,000	AHOP analytics — monthly	ATA/AAA
Engagement	Public-hub interactions/session	Baseline survey	+25%	Web analytics — monthly	FHC
Institutional	Twin data in AAA reports	0	≥2 sections	AAA reports — quarterly	AAA

Note: All performance indicators related to emissions or noise rely on comparative analysis between existing flights (e.g., B737 vs A320). Route or procedure changes are *not* simulated.

Annex B — Data Inventory

The following datasets will be integrated, budget permitting, into the Aruba pilot digital twin, aligned with ACA Level 4 requirements and operational optimization goals:

Flight Operations

- **ADS-B (Automatic Dependent Surveillance–Broadcast):** Continuous aircraft position and velocity data (via ADECS receiver), delivered via JSON/GeoJSON through a webhook or API (format to be confirmed with ADECS).
- **AODB/AOS Milestones:** Gate in/out, pushback, taxi-in/out, take-off and landing times.
- **Aircraft Metadata:** ICAO type codes, engine categories, seat configurations.

Noise Data

- **Fixed Monitoring Stations:** dB(A) readings (LAeq, SEL, Lmax) at strategic community locations.
- **Mobile Monitors (on-demand):** Temporary deployments for hotspot investigations.
- **Historical Archives:** For long-term trend analysis.

Surface Access & Mobility

- **Probe Vehicle / FCD (ISO 23795-1):** Floating car data for congestion and emissions analysis.
- **Lidar Counters:** Vehicle counts at entry/exit points (by type: bus, taxi, private car).
- **Staff Commuting Surveys:** Modal split (car, bike, bus).

Energy & Utilities

- **Electricity Consumption:** Smart meters per terminal section (H, G, F).
- **EV Charging Logs:** kWh consumed per vehicle.
- **Water Consumption:** Monthly supplier invoices (WEB).
- **Waste Data:** Invoices and service provider reports, with breakdown by passenger/staff/tenant sources.

Emissions & Equipment

- **APU/GPU Usage:** Logs and handler-provided data.
- **Ground Support Equipment (GSE):** Telemetry on fleet usage, fuel consumption, maintenance.
- **Airline Fuel Consumption:** Reported values for aircraft operations, where available.
- **Aircraft LTO emissions:** CO₂, NO_x, SO_x, PM emissions calculated using ICAO Engine Exhaust Database factors, based on time-in-mode or measured time data. Requires aircraft engine-type metadata.
APU/GPU emissions are available for a limited set of aircraft/operations and can be included where data permits.

Traveler Engagement

- **AHOP Wallet Metrics:** Adoption rates, offset transactions, user interactions.
- **Public Hub Analytics:** Session counts, feedback submissions.

Annex C — Standards Mapping

The Aruba pilot will align with international and European standards to ensure interoperability, comparability, and trust:

- **ECAC Doc 29 / AEDT:** European and U.S. reference methodologies for aircraft noise modelling.
- **ISO 23795-1:** Standard for probe vehicle/floating car data, applied to surface access.
- **NGSI-LD:** ETSI standard for context information management, enabling real-time, semantic data exchange.
- **MIMs (Minimum Interoperability Mechanisms):** EU/OASC guidelines to ensure portability across local digital twins.
- **ESSIF:** European Self-Sovereign Identity Framework for digital identity and CO₂ verifiable credentials.
- **GHG Protocol / ISO 14064:** Standards for greenhouse gas accounting and reporting.
- **OGC Standards:** Open Geospatial Consortium specifications for geospatial data visualization and services.
- **MQTT/CoAP:** IoT protocols for lightweight, efficient sensor data transfer.
- **OpenAPI Specification:** Common standard for describing and documenting APIs.
- **SDG Indicators:** UN Sustainable Development Goals indicators as reference for sustainability reporting.

Annex D — Stakeholder Engagement Plan

Governance Structure:

- **Pilot Advisory Board:** Led by AAA, includes ADECS, FHC, iLabs, ESRI NL, ATA.
- **Technical Working Groups:** Focused sub-groups on emissions modelling, wallet integration, and noise monitoring.

Engagement Cadence:

- Monthly advisory board meetings.
- Quarterly community update sessions (public hub demos, results presentations).

Channels & Tools:

- Digital Twin Hub feedback forms and dashboards.
- AHOP app surveys and wallet engagement prompts.

- Community newsletters and media releases coordinated with ATA.

KPIs: Number of advisory meetings held, attendance rates, frequency of community inputs integrated into pilot adjustments.

Annex E — MoSCoW Summaries per UC

UC4 – Flights Monitoring & Registration

- **Must:** Automated ADS-B/AODB milestone capture.
- **Should:** Weather/runway condition enrichment.
- **Could:** Public access to 4D flight replays.
- **Won't:** Retain manual milestone entry.

UC5 – Flights & Limitations (OLS)

- **Must:** OLS/tolerance compliance checks.
- **Should:** Public-friendly overlays.
- **Could:** Predictive alerts for non-compliance.
- **Won't:** Static OLS without dynamic updates.

UC6 – Flights & Environmental Impact (Noise)

- **Could:** Flight-by-flight noise calculations.
- **Could:** Complaint clustering analysis.
- **Won't:** Manual-only noise correlation.

UC7 – CO₂ Wallet (AHOP Integration)

- **Must:** Traveler-specific CO₂ footprints stored in wallet.
- **Should:** Offset pathways integrated with local projects.
- **Could:** Gamification and incentive schemes.
- **Won't:** Non-consensual behavioral profiling.

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